EX15-01-001

Lunar L_1 Gateway Conceptual Design Report

Advanced Development Office
Advanced Design Team

October, 2001
Version 1.0

National Aeronautics and
Space Administration

Lyndon B. Johnson Space Center
Houston, TX 77058

Lunar L_1 Gateway Study

Version 1.0

October 2001

Prepared By:

James Geffre
Advanced Design Office

Approved By:

Douglas R. Cooke
Manager, Advanced Development Office

Joyce Carpenter
Manager, Advanced Design Office

FOREWORD

This report describes an element study conducted at the NASA Johnson Space Center during the summer of 2001. The Lunar L_1 Gateway is a functional building block from which a mission strategy for future human exploration is constructed. This particular mission strategy, known as the Gateway Architecture, is an exciting new approach for expanding human space infrastructure beyond Low Earth Orbit and returning humans to the Moon. Central to this strategy is the L_1 Gateway, a spacecraft that will serve as a single, integrated mission-staging platform through which all architecture missions beyond Low Earth Orbit will be performed. Such missions include lunar surface expeditions, assembly and servicing of large astronomical observatories, and various other potential scientific investigations. Described within this document is an assessment of the Gateway's function within the architecture and design details produced for the Gateway element by the JSC Advanced Design Team.

Please direct all correspondence and inquiries about this document to:

Advanced Development Office
Attention: Advanced Design Team Manager
Mail Code EX15
NASA Johnson Space Center
2101 NASA Road 1
Houston, Texas 77058-3696

Project Team Members

This report has benefited from the contributions and advice of many individuals. The individuals listed on the following page assisted in preparing the concepts described in this report and in compiling the words, images, and data used for that description.

Project Management

Joyce Carpenter	Advanced Design Office Manager
Kent Joosten	Architecture Lead
Frank Lin	Element Lead
James Geffre	Lead Systems Engineer

Advanced Design Team

Frank Baiamonte	Power
Cheryl Brown	Environmental Control and Life Support System
Vatsal Bulsara	Structures
Jose Christian	Power
Gerald Condon	Mission Analysis
Tim Cooper	CAD/Vehicle Integration
Ann Davis	Mission Operations
Mike Drever	Structure, CAD/Vehicle Integration
Bryan Fuqua	Risk & Reliability
Robert Hinson	Avionics
Nathan Howard	Robotics
Theresa Lacombe	Human Factors & Habitability
Frank Jeng	Environmental Control and Life Support System
Thomas Paul	Thermal Control System
Todd Peters	Propulsion
Susan Ramsey	Human Factors & Habitability
Jennifer Rochlis	Robotics
Kris Romig	Propulsion
Mike Rouen	EVA
Michael Taylor	Risk & Reliability
Hung Tran	Risk & Reliability

****

CONTENTS

****

FIGURES

TABLES

****

ACRONYMS AND ABBREVIATIONS

ACS	Attitude Control System
ADT	Advanced Design Team
COTS	Commercial-Off-the-Shelf
CRM	Continuous Risk Management
CTV	Crew Transfer Vehicle
DARPA	Defense Advanced Research Projects Administration
ECLSS	Environmental Control and Life Support System
EELV	Evolved Expendable Launch Vehicle
EMU	Extra-vehicular Mobility Unit
EPS	Electrical Power System
EVA	Extra-Vehicular Activity
FAIR	Filled Aperture Infrared Reflector
GCR	Galactic Cosmic Ray
HEDS	Human Exploration and Development of Space
HF&H	Human Factors & Habitability
IBDM	International Berthing and Docking Mechanism
IPACS	Integrated Power and Attitude Control System
ISPR	International Space Station Payload Rack
ISS	International Space Station
JSC	Johnson Space Center
kg	kilogram
kPa	kiloPascal
L_1	Lunar Lagrange point 1
LEO	Low Earth Orbit
m/s	meters per second
MM/OD	Micro-Meteoroid/Orbital Debris
N-m-s	Newton-meter-second
NASA	National Aeronautics and Space Administration
PHA	Preliminary Hazard Analysis
PLSS	Portable Life Support System
PMAD	Power Management and Distribution
psi	pounds per square inch
PV	Photovoltaic
RCS	Reaction Control System
RMS	Remote Manipulator System
SEP	Solar Electric Propulsion
SR&QA	Safety, Reliability, and Quality Assurance
TCS	Thermal Control System
TRL	Technology Readiness Level
V	Volt
W-hr	Watt-hour

****

1.0 Executive Summary

This conceptual design report describes a unique spacecraft design for expanding and maintaining human presence beyond Low Earth Orbit. Missions for human exploration of the solar system are an important part of NASA's future vision, and consequently, reference mission studies are performed to formulate the means by which these missions will be accomplished. These studies, or "architectures", describe the method by which humans leave Earth, perform their objective, and subsequently return to Earth. Recent attention has been focused on a particular architecture for exploration within Earth's Neighborhood known as the Gateway Architecture. This architecture is an innovative approach to achieving new scientific objectives such as returning humans to the Moon and building advanced astronomical observatories in space. Critical to the architecture is the subject of this report, the Lunar L_1 Gateway. The Gateway is the cornerstone in a series of elements that comprise the Gateway Architecture, as it serves as the primary mission staging platform through which these missions will be performed. This platform, the details of which are described within, offers the broad functionality needed to realize these various objectives while minimizing in-space infrastructure.

The Gateway design report is structured into five major sections, including this introduction.

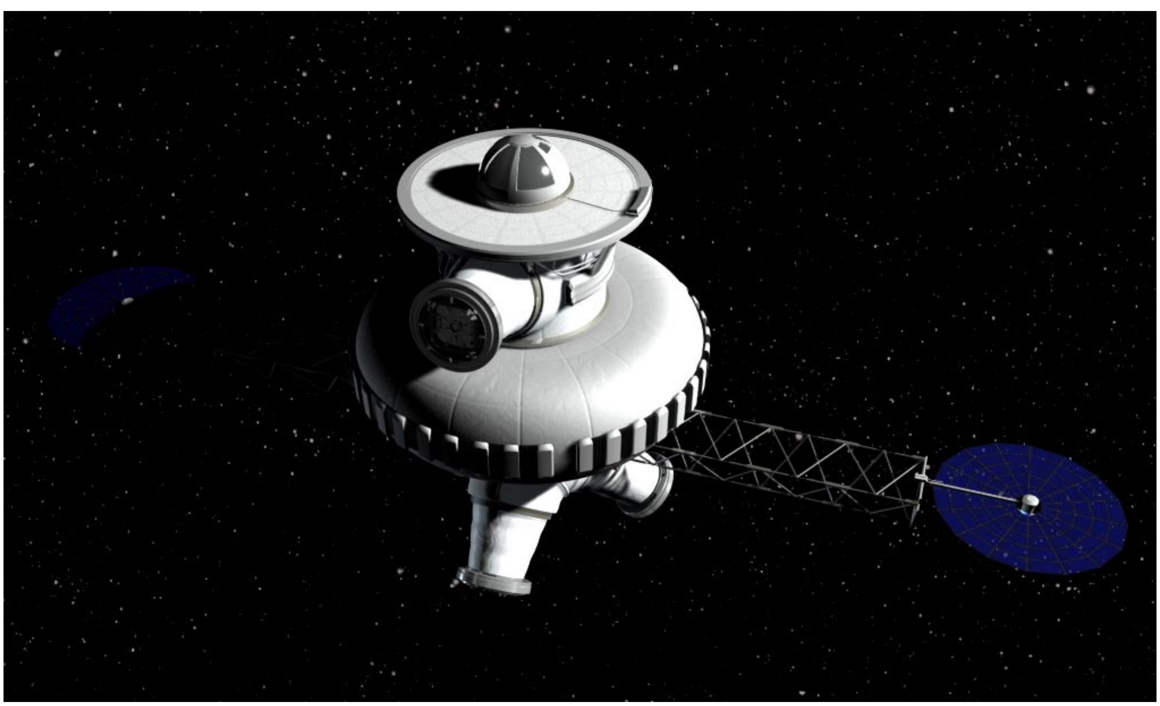
In the next section, the Gateway Architecture is explained in detail, focusing on the Gateway's particular role in and importance to the architecture. Specific attention is paid to missions that directly interface with the Gateway, such as lunar surface and telescope construction missions, and the corresponding vehicle support requirements that are levied upon the Gateway. Accommodating these missions with a single spacecraft has a significant impact on the final vehicle configuration, as will become evident shortly. In addition to architecture requirements, a number of Gateway-specific requirements, constraints, and design goals are described within including rationale for their application. Finally, a complete outline of the Gateway mission is presented from launch from Earth to arrival and operation at Lunar L_1.

Using the Gateway mission outline and top-level requirements, the third section of this report describes in detail the system design specifications chosen to meet this framework. An overall system summary is presented first, including spacecraft-level features such as launch mass and pressurized volume. Also included is detailed rationale for the final Gateway configuration arrived at by the Advanced Design Team and the resupply schedule currently baselined for the Gateway's 15-year lifetime. This is followed by ten subsections describing in precise detail design summaries for the ten Gateway subsystems. Each section, authored by the appropriate discipline lead, features a functional description, a trades-considered overview, the reference design description, and a summary of the discipline's technology needs and design challenges.

In the fourth section is discussed the approach to risk identification and risk management. This process, known as continuous risk management, has been developed from experience gained by performing similar work for human space missions. Continuous risk management is critical to identifying risks at an early stage in the design process when they can typically be eliminated or controlled through design. Also included here is a detailed list of the high-priority risks identified for the Gateway design, an equipment sparing analysis, and overall system success probability analysis. The section then expands upon the findings for specific Gateway subsystems and makes recommendations for future work.

The final section of this report serves to summarize the first iteration on the Gateway element design. A major goal of performing studies such as these is to identify advanced technologies beneficial for future human exploration, the results of which are then used to focus development funding. This section outlines many of the pressing technology needs as implemented in the Gateway with the benefits they offer to the design. Also described are the open issues and forward work matters uncovered during the study. An inevitable part of any conceptual development is multiple iterations on a design, and therefore items identified in this section should be incorporated into future studies of the Gateway.

The Gateway is a critical piece of an innovative overall approach to human exploration beyond Low Earth Orbit. New approaches by architecture designers are leading toward cheaper, more effective strategies for exploration. These results are made evident by the Gateway concept, a single, integrated staging platform for hosting a variety missions while enabling future growth potential. This design incorporates much of the experience gained from NASA's human space flight program and features advanced concepts that may prove beneficial for future exploration. However, the specifics of the element design presented in this report are not intended as a final solution for the Gateway, rather they represent just one technically sound and feasible solution. Different approaches to meeting the same objectives will likely result in drastic changes to the overall configuration and system sizing, however each should be analyzed in full to arrive at the optimal Gateway solution



2.0 Mission Overview

The L_1 Gateway is a crew habitation and mission-staging platform for continuing the exploration of space. Recent scientific discoveries in the lunar polar regions have sparked renewed interest in human exploration of the Moon. In addition, building large astronomical facilities more powerful than NASA's Hubble Space Telescope and upcoming Next Generation Space Telescope (NGST) will require shifting the point of assembly from Earth-based facilities to on-orbit assembly with human and robotic partners. These new opportunities for scientific investigation in Earth's Neighborhood have led architecture designers to take revolutionary new approaches for accommodating these various missions in a sensible integrated fashion. In the past, these destinations were considered on their own basis, with less thought given to how they fit together. This new approach has led to the Gateway concept, which will serve as a single operational staging node for such missions in near-Earth space and beyond.

2.1 Gateway Architecture

The Gateway Architecture is a near-Earth mission strategy for returning humans to the Moon and expanding human infrastructure in space. This architecture targets "100-day class" missions, the next design reference point beyond present day low-Earth orbit exploration.[1] The cornerstone of the architecture is the emplacement of a mission-staging platform near the Moon, specifically at the Lunar L_1 Lagrange point. This facility will serve as a "gateway" to future human exploration of space, including the lunar surface, other Lagrange points, and Mars. In the context of the Gateway Architecture, the term "Earth's Neighborhood" is used to encompass Earth, the Moon, and the collinear Lagrange points Lagrange points of the Sun-Earth system. More specifically, it refers to all potential destinations within a 1.5 million km radius from Earth.

A primary goal of the Gateway Architecture is to enable both short-duration and extended-stay exploration of the entire lunar surface. Utilizing the collinear Earth-Moon L_1 Lagrange point as a mission staging node allows access to all lunar latitudes for essentially the same transportation costs while providing a continuous launch window to and from the lunar surface.[2] Though a lunar orbit rendezvous approach requires less total ΔV than Lagrange point rendezvous, launch phasing constraints are a significant concern. For rendezvous in lunar orbit, the ascent window opens when the orbital plane rotates over the landing site. In the case of high-latitude sites on the Moon that are of particular scientific interest, launch opportunities may be separated by as much as fourteen days. However, as the Lagrange point maintains a fixed position relative to the lunar surface, launch opportunities are continuously available.

Future large aperture Gossamer telescopes will require on-orbit assembly, calibration, and servicing, and as a result, extensive infrastructure to support these tasks. The unique capabilities of the L_1 Gateway may offer an integrated solution to this problem. While the Space Shuttle offers robotic and EVA capabilities, maneuverability, and workspace freedom, it lacks the long-duration crew sustenance capability of ISS. The goal of the L_1 Gateway concept is to incorporate all of these functions into a single integrated spacecraft.

In addition, telescope assembly at Lunar L_1 can solve some of the environmental and operational concerns of Low Earth Orbit. Contamination of the hypersensitive telescope instruments and reflector surfaces is a major concern, and it is doubtful that the Shuttle or ISS could meet these requirements. Adherence of atomic oxygen found in LEO may also be a contamination concern. Construction in LEO implies a high risk of micrometeoroid and orbital debris impact, a risk that is greatly reduced at L_1. Finally, this destination offers a more attractive thermal environment for telescope assembly. An outgassing and bake-out phase may be desired to eliminate any lingering contaminants from the telescope structure, thus requiring a sustained high-temperature environment. On the other end of the spectrum, telescope instruments must be passively cooled to cryogenic temperatures for operation. As Lunar L_1 is located in a deep space environment, use of the FAIR sunshield can achieve such temperatures for instrument testing. The temperature environment of Low Earth Orbit involves constant orbital day/night cycling and thermal albedo from Earth, therefore is less likely to satisfy telescope assembly requirements.

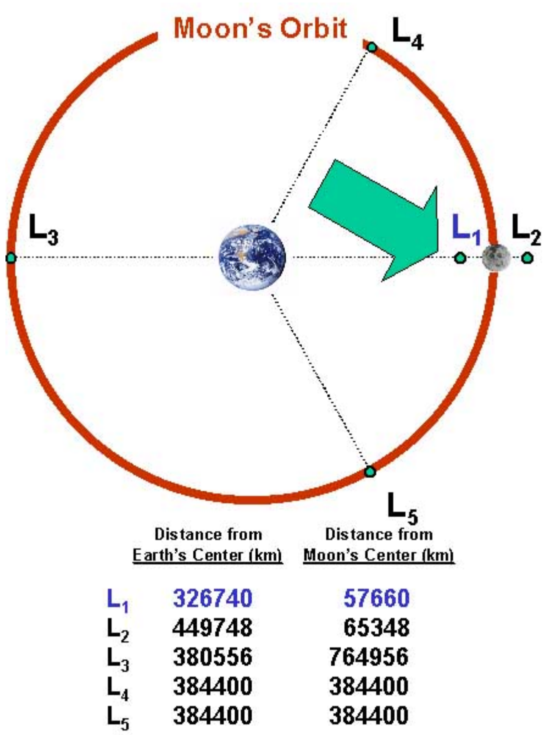


Figure 2.1 Earth-Moon Lagrange Points

For reference, the five Lagrange points of the Earth-Moon system are illustrated in Figure 2.1. Note the location of Lunar L_1, the final destination of the Gateway, with respect to Earth and the Moon.

2.1.1 Architecture Groundrules and Constraints

A crew of four has been baselined for all Gateway Architecture missions. Lunar surface and Gateway EVA operations require the crew to work in pairs of two, and it was assumed that the two pairs of two would alternate each EVA. However, the baseline of four crewmembers per mission may not be a hard constraint, and further analysis should be performed to determine the impact of this decision.

For all launch needs of the Gateway Architecture, it has been assumed that only vehicles currently in operation or scheduled for near-term operation will be considered. This category includes the U.S. Space Shuttle and the Evolved Expendable Launch Vehicle (EELV) family under development in the space lift modernization program. To achieve the necessary minimum payload capacity to LEO, moderate augmentations to the EELV launchers have also been considered. A maximum capability of 35,000 kg to ISS orbit and 6 m static payload diameter is assumed for this study.

Initial planning for the Gateway Architecture has been centered on a first mission date of 2011. It is the desire of the astronomical observatories program to begin telescope construction at Lunar L_1 in this timeframe, therefore all Gateway-related infrastructure must be in place. This decision has a tremendous impact on technology development and system selection. It was assumed that five years would be required to advance hardware technology to "flight-proven" status (NASA technology readiness level

(TRL) nine), assuming that technology or system prototype had been previously tested successfully in a relevant environment (TRL 6). Therefore, to achieve the initial Gateway operational capability date of 2011, all technologies must be advanced to a TRL of six by 2006. Similarly, all launch vehicle systems must be in operation by 2011.

2.1.2 Architecture Design

The Gateway Architecture is illustrated in Figure 2.2. The architecture centers on utility of the Lunar L_1 Lagrange point and the associated emplacement of the Gateway at that location.

Crew transfers are accomplished with high thrust, low efficiency chemical propulsion systems to reduce trip times and minimize exposure to the hazardous environment of space. Crew destinations in the Gateway Architecture include Lunar L_1, the lunar surface, and Mars. For less time-critical transfers such as cargo payloads, delivery is baselined with electric propulsion. Electric propulsion offers an order-of-magnitude increase in system efficiency at the cost of greater trip time. However, the penalty paid for longer trip time is greatly offset by the reduction in total architecture mass possible with low-thrust systems such as solar electric propulsion.

Missions to the Gateway will commence with a crew transfer from the International Space Station to Lunar L_1 using a Crew Transfer Vehicle (CTV). The CTV follows a minimum-energy trajectory, requiring six days to go from ISS undocking to Gateway docking. For telescope assembly or lunar surface missions from the Gateway, the respective payloads will be delivered prior to crew arrival via electric propulsion stages. In the case of a telescope construction mission, the telescope is autonomously delivered upon assembly completion to its final destination, Sun-Earth Lagrange point two, via low-energy transfer. An emerging field in orbital mechanics known as invariant manifold analysis has identified potential trajectories between Lagrange points at very little propellant cost.[3] Utilizing the L_1 Gateway as a construction facility for Gossamer telescopes will enable such low cost transfers while consolidating in-space infra-

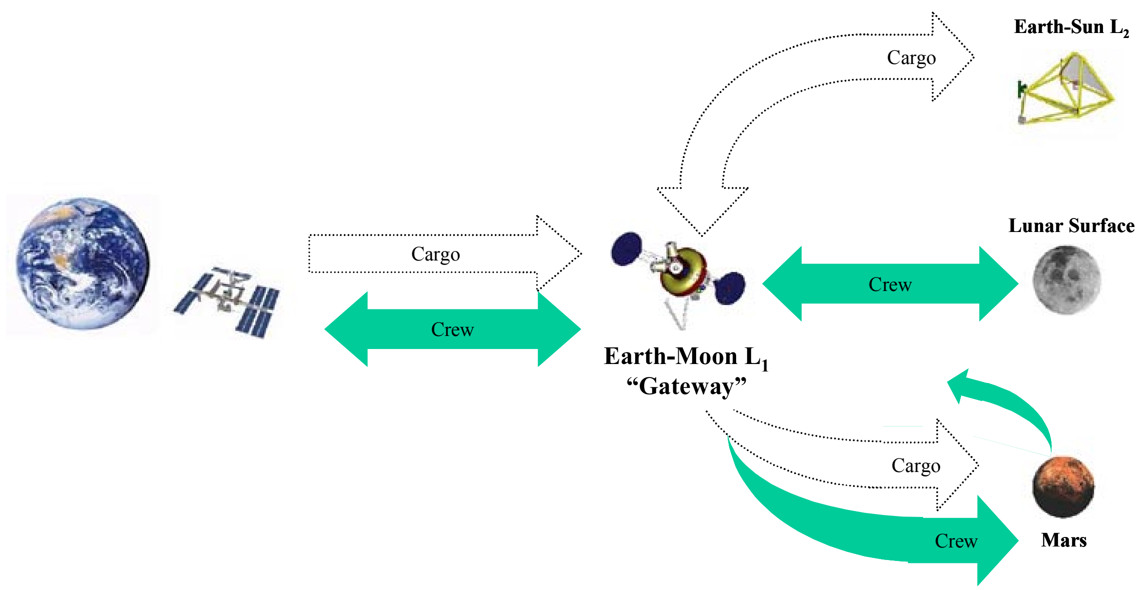


Figure 2.2 Gateway Architecture

structure.

While telescope missions are performed at the Gateway, a lunar mission involves entering a docked Lunar Lander and descending to the surface. Descent is accomplished via chemical propulsion, and the crew can stay up to three days on the lunar surface. However, in the case of a mission to the extended-duration Lunar Habitat, surface stays up to thirty days are possible. Finally, the crew returns to the Gateway with the Lander ascent stage, leaving the spent descent stage on the surface. Once at the Gateway, the CTV is again used to return the crew to the ISS.

2.2 Gateway Requirements, Constraints, and Design Goals

The following sections describe the driving requirements levied upon the Gateway design with associated rationale for their origin. More detailed top-level requirements, constraints, and design goals are outlined in Appendix A.

2.2.1 Top-Level Requirements

The driving top-level requirements for the Gateway are listed below, with further elaboration and rationale following.

- Support four missions per year
- 15-year design lifetime
- Support crew of four
- Protect crew and spacecraft from all operating environments
- Support three concurrently docked visiting vehicles

As derived from Gateway Architecture groundrules, the L_1 Gateway will serve as a staging platform for crews of four performing lunar surface excursions, telescope assembly and servicing, and a host of other potential missions. For this iteration of the Gateway study, four missions will be baselined per year, with two devoted to telescope construction and two for lunar surface expeditions. Further assessment of the Gateway Architecture should re-examine this requirement.

The Gateway has been designed to provide an operating lifetime of at least fifteen years. Though lunar mission planning in the Gateway Architecture is currently limited to a five-year timeframe, the large complex science facilities program will require at least fifteen years of support from the Gateway. This requirement is driven by the considerable number of planned observatories to be assembled at Lunar L_1 and subsequent telescope servicing needs.

The Gateway must be capable of simultaneously supporting three visiting vehicles, thus driving structural configuration and number of docking ports. Preliminary mission planning has envisioned a Lunar Lander, Crew Transfer Vehicle, and a logistics module potentially being docked to the L_1 Gateway at the time of a lunar mission. Since crew will be required to unload resupply items from the logistics module, it will occupy a docking port during either a lunar or a telescope mission.

Similar to all human spaceflight vehicles, the Gateway must protect the crew and systems against the dangers from natural and induced operating environments. These environments, discussed further in Section 2.3, include launch, Low Earth Orbit, transit to Lunar L_1, and Lunar L_1. For the launch phase, the systems must withstand substantial axial and lateral loading imparted by the launch vehicle. Further, the Gateway will be evacuated during launch; therefore, systems must survive and operate in this environment.

All in-space flight segments are subject to hypervelocity impact from micrometeoroids and orbital debris (MM/OD), though the predominant source of impact, orbital debris, is only a concern in LEO. The structure of the Gateway is designed to protect to a 95% probability of no penetration over the entire 15-year lifetime. This requirement is commensurate with those levied by the International Space Station program, thus was deemed acceptable by the Gateway design study leads.

Another environmental concern is radiation damage to the crew. For the Gateway, the requirement is to provide sufficient radiation protection against solar particle events (SPE) and galactic cosmic rays (GCR) to a 97% probability of not developing fatal cancer. This figure is traditionally adopted by exploration mission planners, however acceptable radiation risk is an issue that needs to be addressed at a programmatic level. A better understanding of the deep space environment and destructive mechanism of radiation will be needed to quantify and design to any protection requirement.

Additional top-level Gateway requirements and rationale are found in Appendix A.

2.2.2 Constraints

Initial studies have revealed that transportation costs for major elements of the Gateway Architecture quickly becomes prohibitively expensive when using traditional chemical propulsion systems. Electric propulsion has been identified as an implementation for delivery of unmanned cargo elements from LEO to destinations of interest - Lunar L_1, Low Lunar Orbit, Earth L_2. For this architecture, reusable solar electric propulsion stages have been baselined for cargo transfer. Therefore, delivery of the Gateway from LEO to Lunar L_1 will be performed via solar electric propulsion.

2.2.3 Design Goals

A driving goal of the L_1 Gateway design is to serve as a technology testbed for future human exploration beyond Earth's neighborhood. Demonstrating the operability of system technologies prior to use can drastically reduce the cost and risk of such missions. Previous studies have identified key thrusts in the areas of advanced habitation, life support, in-space transportation, and power. For example, inflatable structures can provide large habitable volumes and integrate passive radiation protection methods while minimizing mass and packaged volume. Closed-loop life support is an enabling technology for long-duration spaceflight by radically reducing total consumable mass requirements. A routine EVA capability will be needed for robust exploration of planetary surfaces. It is in these areas and others that the focus of the Gateway design is placed, and wherever possible, such systems have been selected.

As in all human exploration studies, assuring crew safety, reliability, and operability is the highest priority. Systems should be designed to use non-toxic substances whenever possible. To optimize for crew operation, systems should minimize complexity to increase reliability and ease of maintenance. Gateway hardware should be designed to incorporate new technologies as they become available. These goals have a significant impact on final system design, and though sometimes conflicting, must be satisfied to fulfill the intended role of the L_1 Gateway.

2.3 Mission Design

The Gateway mission will begin with launch from Cape Canaveral Air Force Station (CCAFS) to a low-Earth orbit of 400 km altitude and 28.5° inclination. Launch (step

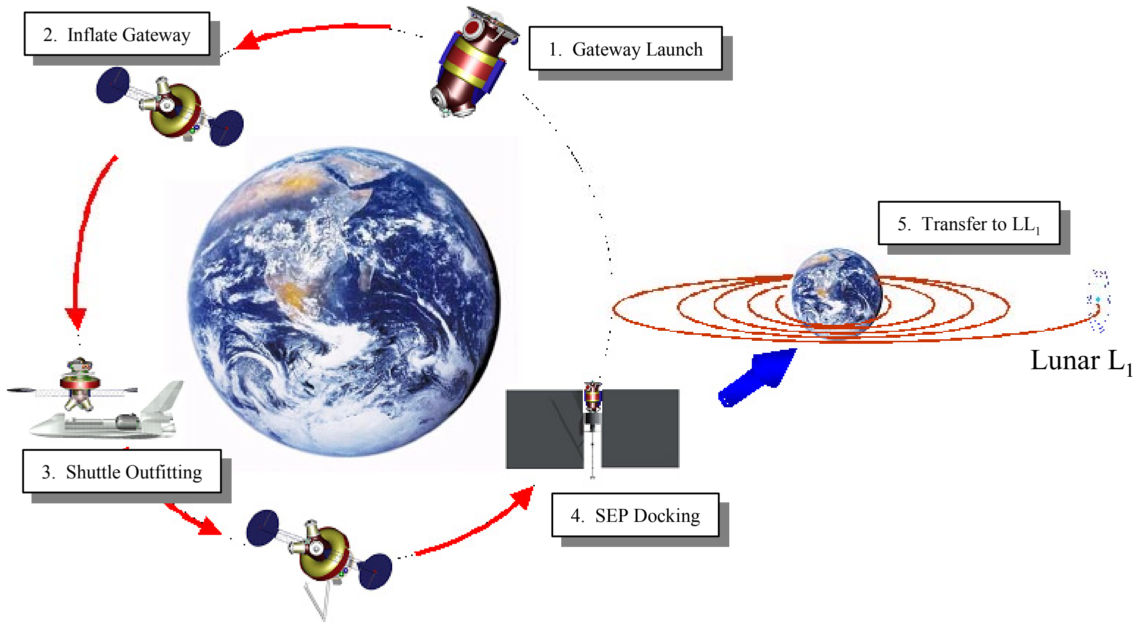


Figure 2.3 Gateway Mission Events from Launch to Lunar L_1

1 of Figure 2.3) is baselined on the Delta IV Heavy "Exploration Class" booster, a proposed unmanned heavy-lift variant of the Boeing Delta IV EELV family.[4] It was expected that the additional payload volume and mass capability of this launch vehicle would be required for the Gateway, therefore was baselined for initial study. However, future studies should further examine the possibility of using the Space Shuttle for launch. Once in orbit, the Gateway will begin autonomous system start-up and check out. The spacecraft is then pressurized and the inflatable section is inflated (step 2), with photovoltaic arrays deployed to provide power to the Gateway.

Shortly following launch of the Delta IV Heavy, a Space Shuttle will then launch and dock with the Gateway in LEO (step 3). It was determined that an outfitting mission for the spacecraft will be required, a task for which the Orbiter is well suited. As the inflatable section of the Gateway will be uninflated during launch, all on-board equipment must be arranged within the core pressure shell. However, the final cabin layout arranges equipment throughout the entire pressurized volume, a task that the Shuttle outfitting crew will perform. Rather than preparing the Gateway for operation once on-station at Lunar L_1, a dedicated mission in LEO is far more efficient and less costly.

In addition to arranging equipment throughout the cabin, the outfitting crew will be tasked with testing equipment to ensure proper function. Malfunctions identified during autonomous system start-up can be corrected with the outfitting, and any subsequent problems can be rectified with the first CTV mission at L_1. Lessons learned from ISS construction may be very beneficial in focusing Gateway outfitting tasks.

Finally, certain vital systems cannot be brought up with the Delta IV Heavy launch. This is due to volume limitations within the fairing and an evacuated spacecraft volume during launch. Rather, equipment not rated for operation in a vacuum will be launched on the Shuttle and transferred to the now-pressurized L_1 Gateway. To accommodate the cargo volume necessary for the mission, it is recommended that the Shuttle be outfitted with a double SpaceHab module featuring an International Berthing and Docking Mechanism (IBDM) for compatibility with the Gateway. This ensures no Orbiter modification will be required.

Upon completion of the outfitting mission, the Shuttle will undock from the L_1 Gateway and return to Earth. A Delta IV Heavy will then launch a Solar Electric Propulsion (SEP) Stage to LEO for rendezvous and docking with the L_1 Gateway as seen in step 4 of Figure 2.3. Subsequently, this element stack will begin autonomous transfer (step 5) to Lunar L_1. The SEP Stage slowly spirals outward from LEO, and arrives at Lunar L_1 after approximately 180 days.

After undocking from the SEP Stage in the vicinity of Lunar L_1, the Gateway will position itself at the Lagrange point with its on-board station-keeping system. It was determined that the SEP Stage would not remain attached to the Gateway to provide power, attitude control, and station-keeping, rather would return to LEO for refueling and reuse. The factors that led to this decision were that the SEP Stage's large deployed array area would adversely affect Gateway vicinity work areas and that the vehicle was a resource too valuable to not be reused. The SEP Stage arrays provide an order-of-magnitude greater power than needed by the Gateway, which is a requirement that can be easily met by a dedicated on-board system.

Once on-station at Lunar L_1, the Gateway will begin performing its intended role as a mission staging and crew habitation facility. The L_1 Gateway will host lunar surface expeditions and telescope construction missions for the remainder of its operational lifetime, at the rate of four missions per year. The details of these missions and accompanying requirements for the Gateway are described below, and illustrated in Figure 2.4.

2.3.1 Lunar Surface Mission

As previously discussed, the Gateway Ar-

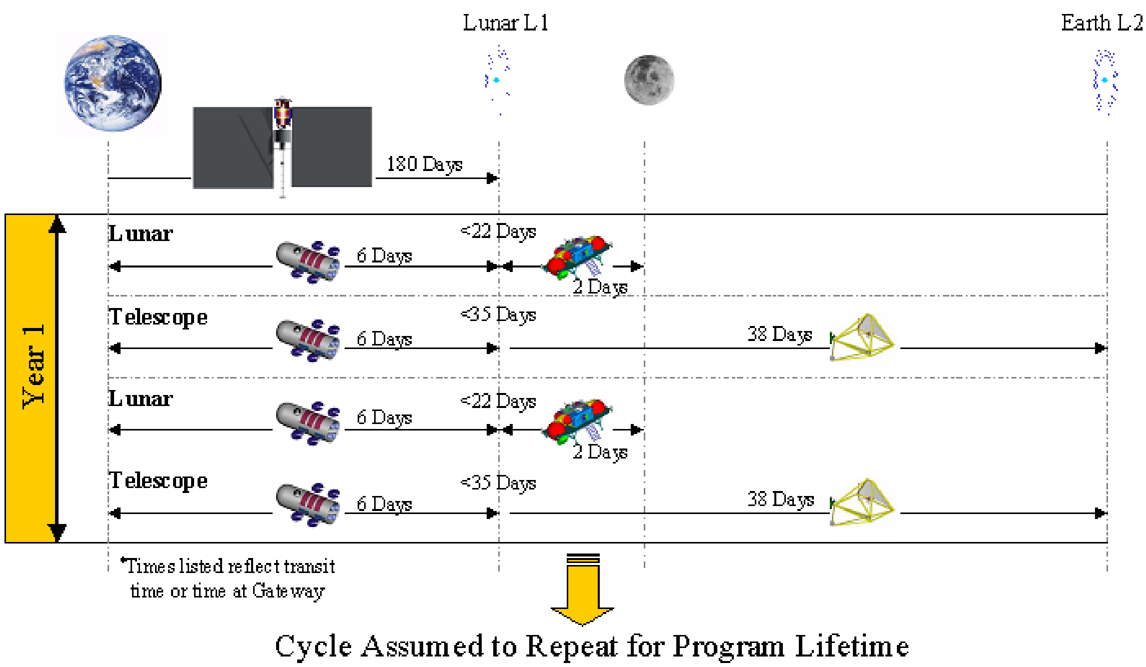


Figure 2.4 Gateway Mission Cycle Baseline

chitecture utilizes the L_1 Gateway as a staging node for lunar surface excursion missions. Current architecture planning calls for two surface missions to be conducted per year.

2.3.1.1 Mission Scenario

For the lunar surface mission scenario, a Lunar Lander will be pre-deployed and docked to the Gateway prior to mission commencement. Upon arrival of the CTV, the crew of four will require forty-eight hours to prepare for lunar surface departure. Transferring to the Lunar Lander, the crew will then perform an 8-day mission away from the Gateway, spending three days on the lunar surface. In the case of the long-duration stay at the Lunar Habitat, the crew will spend thirty days on the lunar surface, for a total mission time of thirty-five days. The Lunar Lander will return the crew to the Gateway.

Upon mission completion, the spent ascent stage of the Lunar Lander will autonomously undock from the L_1 Gateway and be disposed of in a final orbit to be determined. Figure 2.5 depicts the Lunar Lander and CTV docked to the Gateway.

2.3.1.2 Requirements

The Gateway requirements for supporting lunar surface missions are enumerated below.

- Provide crew habitation resources for twenty-two non-consecutive days per lunar mission
- Provide vehicle support to the Crew Transfer Vehicle (CTV) for up to fifty-seven consecutive days per lunar mission
- Provide vehicle support to the Lunar Lander for up to sixty consecutive days per lunar mission
- Support two lunar surface excursions per year

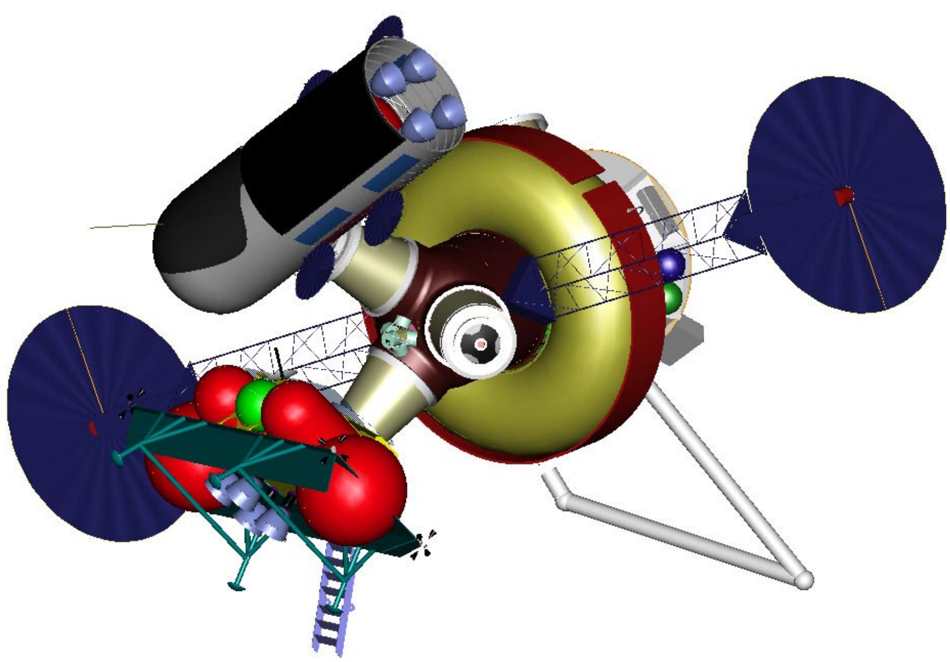


Figure 2.5 Gateway with CTV and Lunar Lander Docked

After their return to the Gateway, the crew may require up to nine days awaiting the first return opportunity to ISS, and an additional ten days if the first return opportunity is missed or unavailable. As a result, the Gateway must provide life support for a total of up to twenty-two non-consecutive days per lunar mission including contingency scenarios. While the crew is on the lunar surface, the CTV will remain docked to the Gateway. For the constraining case of a long-duration mission to the Lunar Habitat, the CTV will require vehicle support for up to fifty-seven days.

Prior to mission start, a Lunar Lander will be delivered to Lunar L_1 and autonomously docked to the Gateway. The current Gateway Architecture plans for this event to occur two months prior to crew arrival in the CTV, thus the Lunar Lander will require vehicle support during this period.

2.3.2 Telescope Construction Mission

The Gateway has been identified as a potential platform for the construction and servicing of large astronomical science facilities. As conceptual studies for these observatories are on-going and lack detailed definition, a generic yet robust capability has been designed for the Gateway. For the purposes of this study, a proposed concept for the Filled Aperture Infrared Reflector (FAIR) Telescope[5] was used as reference.

Construction of Gossamer telescopes is expected to fall within a broad spectrum of task complexity and frequency. Assembly will likely be accomplished through an optimal combination of human EVA and robotic capabilities. Whereas robotic systems are generally suited to more frequent, less complex tasks, humans are best applied in non-repetitive, non-linear situations. NASA is currently performing studies to examine optimized assembly of the FAIR telescope, the results of which can be used to influence the L_1 Gateway design.

Further detail on the present robotic and EVA capabilities of the Gateway is found in Section 3.2 – Subsystem Design.

2.3.2.1 Mission Scenario

In the telescope construction scenario, a cargo vehicle carrying the stowed assembly components will be docked to the Gateway prior to crew arrival in the CTV. Upon arrival, the crew will then conduct a 15-day mission constructing the FAIR telescope. Though specific tasks to be completed during this period are undefined, it is assumed that multiple EVA sorties will be required in concert with telerobotic operations conducted inside the spacecraft. A view of the Filled Aperture Infrared Reflector Telescope concept is provided in Figure 2.6.

2.3.2.2 Requirements

The top-level requirements for conducting two telescope construction missions per year

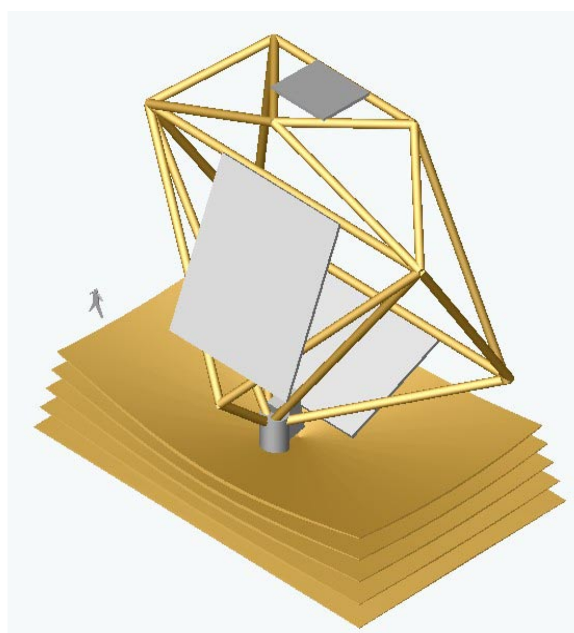


Figure 2.6 FAIR Telescope Concept

at the Gateway are as follows.

- Provide crew habitation resources and CTV vehicle support for up to thirty-five consecutive days per mission
- Allow eight 8-hour EVA sorties per mission
- Provide robotic systems to aid in assembly and servicing
- Support two telescope construction missions per year

Upon mission completion, the crew may spend up to eight days awaiting their first return opportunity to ISS, and an additional ten days if the first return opportunity is missed or unavailable. Including missed departure opportunity contingency scenarios, a crew will require habitation support for up to thirty-five days per telescope construction mission. Detailed mission planning may reduce the wait time prior to initial ISS return opportunity, however that is currently unavailable. For the purposes of this study, it has been assumed that fifteen days will be dedicated for telescope assembly, thus driving total support time requirements.

2.3.3 Additional Missions

The L_1 Gateway may also be used as a platform for a host of additional missions, the inclusion of which may be possible as detailed definition becomes available. By virtue of its constant position relative to the Earth-Moon system, the Gateway may potentially be used as a communications relay to offload the already over-subscribed Deep Space Network or as a platform for power beaming to in-space assets. Moreover, the environment of Lunar L_1 provides a deep space analog within Earth's neighborhood, thus enabling opportunistic biological and material exposure investigations. Such missions could be invaluable in preparing humans for long-duration expeditions beyond Low Earth Orbit.

2.4 References

[1] National Aeronautics and Space Administration. (2001). Human Exploration & Development of Space Strategic Plan. Washington, D.C.

[2] Bond, V.R., Sponaugle, S.J., Fraietta, M.F., & Shonn, F.E. (1991). Cislunar Libration Point as a Transportation Node for Lunar Exploration, AAS-91-103. AAS/AIAA Spaceflight Mechanics Meeting. Houston, TX.

[3] Joosten, B.K. (2001). Human Space Exploration in "Earth's Neighborhood" – Strategy and Architectural Approach, AIAA 2001-4561. Space 2001 Conference and Exposition. Albuquerque, NM.

[4] Boeing Presentation to JSC Exploration Office, August 2001.

[5] JPL Advanced Projects Design Team. (2001). FAIR-DART Opt. #1, 2001-08. Pasadena, CA.

3.0 System Design

The following sections detail design of the L_1 Gateway as performed by the JSC Advanced Design Team.

3.1 Gateway Overview

The Gateway is a self-contained spacecraft stationed at Lunar L_1 for staging missions in Earth's Neighborhood. The 275-m^3, 22 metric ton hybrid inflatable spacecraft is launched to LEO on an EELV and is delivered to LL_1 via a Solar Electric Propulsion Stage, then remains on-orbit at the Lagrange point for 15 years. It provides 12 kW of peak power for its systems, simultaneously hosts up to three visiting vehicles, and offers a robust EVA and robotic capability for in-space operations. Systems have been designed to demonstrate advanced technology and for "closing the loop" to minimize resources and resupply needs, though basic resupply will occur on 6-month and 2-year intervals. Additional system details and illustrations are included in the following sections.

3.1.1 Spacecraft Specifications

The L_1 Gateway provides 275 m^3 of pressurized volume to the crew, with approximately 60 m^3 occupied by internal system hardware. Additional volume is occupied due to cabin layout constraints, though the Gateway still provides a comfortable environment for its crew. For missions similar in scope to the Gateway (4 crewmembers, 30-day stay), a minimum habitable volume of 60 m^3 is required. However, as the Lunar Lander and CTV are both volume-constrained spacecraft, the Gateway will be used as a crew oasis, therefore providing more habitable space than the minimum requirement was recommended. As reference, NASA's Skylab project provided 361 m^3 of volume for a 3-person, 84-day mission.

Table 3.1 presents a mass and volume summary of the Gateway. The total launch mass

Lunar L1 Gateway	Launch Mass		Equip Vol
	% of Inert Mass	Total	Total
1.0 Power System	8%	1335	27.5
2.0 Avionics	2%	251	0.6
3.0 ECLSS	17%	2852	15.9
4.0 Thermal Control System	4%	664	3.4
5.0 HF&H	15%	2507	15.0
6.0 EVA Systems	5%	900	9.7
7.0 Structure	44%	7354	0.2
8.0 Robotics	1%	227	6.8
9.0 Attitude Control System	2%	318	0.3
10.0 Propulsion (RCS)	1%	176	1.3
Subtotal (Inert Mass only)	**100%**	**16,584 kg**	**81 m^3**
30% Margin (Inert System)		4975	15.2
11.0 Propellant (RCS)		1268	0.0
12.0 Crew		0	0.0
Total		**22,827 kg**	**96 m^3**

Table 3.1 Gateway Mass Summary

is 22,827 kg, which is significantly less than the 35,400 kg capability of the Delta IV Heavy “Exploration Class” launch vehicle. A 30% mass margin has been added to all system inert mass (non-propellants) to cover design uncertainties and future growth. Following completion of the Shuttle outfitting mission, 800 kg will have been added to the Gateway, which is the final configuration that the SEP Stage must deliver to Lunar L_1. This mass includes the Remote Manipulator System and other items that cannot be launched on the EELV, therefore must be outfitted from the Shuttle.

Gateway resupply recurs on a 6-month and 2-year schedule. Shelf-life critical items such as food, clothing, and medical supplies will be provided for two missions to the Gateway and then must be refreshed. Food and clothing is typically customized to a particular crew’s preferences, therefore providing these greater than two missions in advance would require significant planning. In addition to these concerns, implementing a 6-month resupply schedule may enable synergistic cost-saving benefits. As the Gateway Architecture calls for a Lunar Lander to be delivered every six months, its pressurized volume may potentially be utilized as a cargo transport. Resupply items can be packed inside the Lander and unloaded by Gateway crews, however determining the feasibility of this will require further analysis. The total 6-month resupply need amounts to 805 kg and 3.9 m^3.

Every two years, cryogenic methane and oxygen must be replenished for the propulsion system as well as atmosphere supply and potable water for the ECLSS. Vehicle support items such as translation aids and suit batteries for the EVA system must also be refreshed. Delivery of the 2,824 kg and 7.6 m^3 for 2-year resupply is baselined on a currently unknown dedicated cargo carrier, and future efforts should be concentrated on

Resupply	Mass		Volume	
	6-month	2-year	6-month	2-year
ECLSS	0	741	0	2.1
HF&H	619	0	3.0	0
EVA	0	334	0	2.5
Propulsion	0	122	0	1.3
30% Margin	186	359	0.9	1.8
Propellant	0	1268	0	0
Total	**805 kg**	**2,824 kg**	**3.9 m^3**	**7.6 m^3**

Table 3.2 Gateway Resupply

design of this vehicle. A summary of the Gateway resupply needs is found in Table 3.2.

To determine the peak power and energy storage requirements, a power profile analysis was performed for all aspects of the Gateway mission. Using system component current and power duty cycles, a total energy and correspondingly, an average power requirement, was determined for each phase. From the analysis, the constraining phase was a telescope assembly mission, during which an average power of 8,000 W is required. To cover power peaking and system uncertainties, an additional 50% was added for a total Gateway peak power requirement of 12,000 W. The Gateway power profile is included as Figure 3.1.

For energy storage, 91 kW-hr will be provided, or 7,000 W of continuous power for

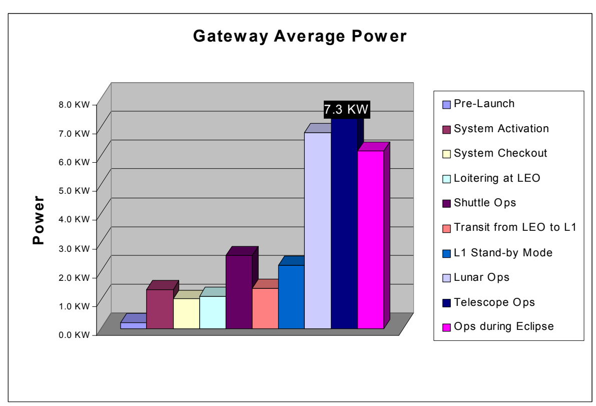


Figure 3.1 Power Profile

13 hours. Approximately every six weeks, an occultation period at LL_1 occurs when the limb of Earth or the Moon crosses that of the Sun. An occultation period of 13 hours was found during maximum lunar inclination, therefore was used for sizing of the energy storage system. These periods hinder the ability of the photovoltaic arrays to provide power, so an alternate source of energy is necessary, one that is not dependent upon the Sun. In reality, the loss of sunlight would follow a ramp-down behavior, or in some cases the Sun may continue to shine throughout the entire occultation period, however 13 hours was adopted as a conservative, absolute worst-case approach. One option for reducing this requirement would be to plan Gateway missions to avoid these periods, though this was not pursued further. In determining the amount of power required during eclipse, the following philosophy was adopted. Systems that were not considered mission-critical would not be operated, though any significant degradation in mission performance capability would not be tolerated. This led to an average occultation power requirement of 7,000 W.

3.1.2 Configuration

Three competing options for the Gateway primary structure were considered: a rigid pressure shell similar to an ISS module, a purely inflatable structure, or a hybrid structure that utilized both rigid and inflatable elements. For long-duration human spaceflight, a large habitable volume will be required for maintaining positive crew welfare. Inflatable habitation systems may be a promising solution to this need by providing significant volume while minimizing total launch mass and packaged volume. As a primary design goal of the Gateway is to demonstrate such advanced technologies for future human exploration, an inflatable section was used to provide the primary habitable volume. However, such a structure presents major design challenges when massive external load-bearing systems must be attached. For the Gateway, a number of systems, such as an EVA work platform, docking ports, a robotic arm, photovoltaic arrays, and others must be attached to the exterior structure. These needs, coupled with the desire to use inflatable technologies, led to a hybrid structure design for the Gateway. The hybrid Gateway structure is illustrated in Figure 3.2. A core pressure

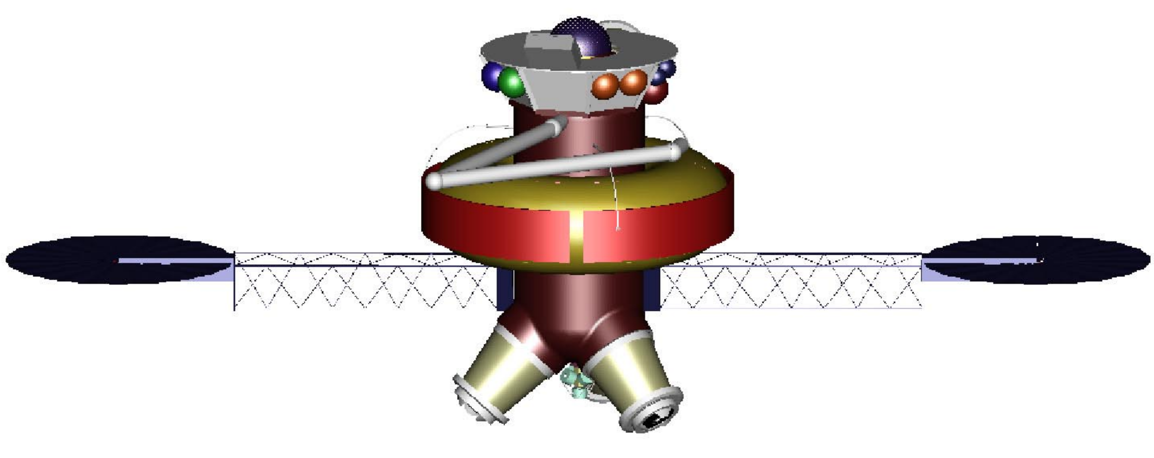


Figure 3.2 Hybrid Gateway Configuration

shell will provide rigidity for attaching external components and packaging systems during launch, while an inflatable section will provide a large habitable volume for the crew.

It was determined that the Gateway must provide three docking ports to support visiting vehicles. In the case of a lunar surface mission staged from the Gateway, a Lunar Lander and the Crew Transfer Vehicle will be simultaneously docked. Additionally, as the Gateway will require resupply, and crew will be needed to unload equipment to the Gateway, a logistics resupply vehicle may also be docked during a lunar mission. Therefore, three separate docking ports are required, with the third baselined for resupply or to provide redundancy to the other two. As telescope construction will require a nominal, frequent EVA capability, a fourth adapter is featured in the design to serve as a dedicated airlock and primary egress path. In the case of a failure by one of the docking ports, the airlock may be outfitted with an IBDM to support docking, though only a simple hatch will be present for nominal operation. The total pressurized volume of the airlock and three docking ports is 25.6 m^3.

An issue faced in determining the final Gateway configuration was arrangement of the docking ports and airlock. In docking operations, a visiting vehicle should not approach its target in the direction of the Sun to avoid visibility issues. Therefore, the three docking ports arranged in a tripod configuration will face the Sun, and vehicles will approach in the opposite direction. For telescope assembly and servicing, a large unobstructed workspace is required, thus the EVA work platform was placed opposite from the three docking ports. This avoids the need to translate around any docked vehicle. Finally, the location of the airlock was placed to minimize crew translation distance during an EVA, which meant being as close to the EVA work platform as possible. These decisions drive the configuration of the Gateway.

The core pressure shell is used to package critical systems within the Gateway and provides mounting locations for external hardware. It consists of a 4 m diameter, 6.5 m long circular cylinder with capped hemispherical ends for a total pressurized volume of 111 m^3. One end cap houses the tripod docking ports, while the opposite end contains an airlock, a cupola, and connects to the EVA work platform. A minimum circular passageway of 1 m is maintained along the length of the core for crew translation. To provide entrance to the inflatable volume, a section of the cylinder skin has been removed. Near the docking port end of the cylinder, system hardware from the ECLSS, TCS, power, and avionics is closely packaged to share resources and minimize acoustic dampening material. A view of this hardware packaged within the core is provided in Figure 3.3.

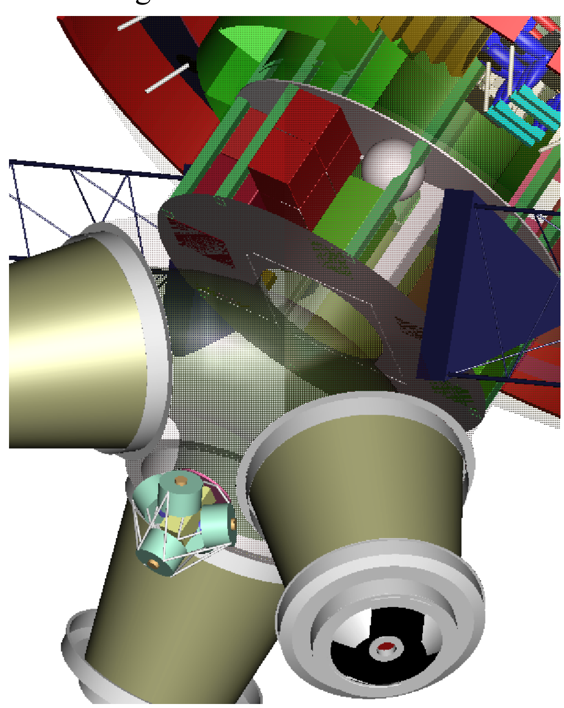


Figure 3.3 Docking Ports and Core

At the EVA end of the Gateway core, a cupola window provides full viewing of the EVA work platform from the Robotics Workstation, and crew leisure viewing during off-duty hours. Human rating requirements for NASA spacecraft dictate that windows must be provided for these functions. In addition to the airlock placed here, a dedicated area is used for space suit stowage, suit donning and doffing, and suit recharge. Necessary EVA and robotics equipment is packaged in this section of the Gateway, as illustrated in Figure 3.4.

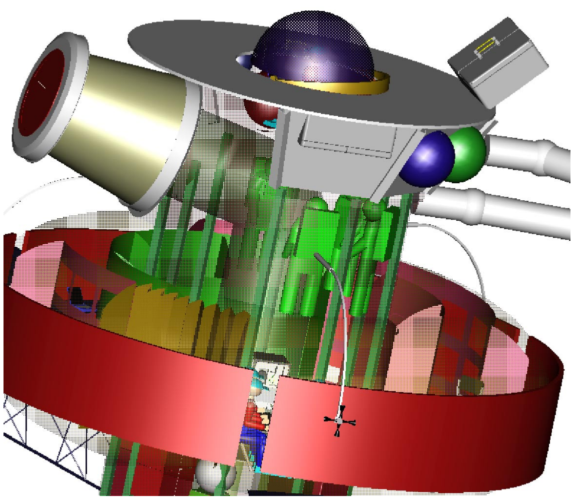


Figure 3.4 EVA Prep and Robotics Area

In order to meet the Gateway volume requirements, only a single floor is needed in the inflatable section. For the inflatable volume, a torus section was selected to minimize wall thickness and structure mass. A section of this type provides the most volume for a given surface area, therefore reduces total mass. The torus section will be tightly packed against the core pressure shell during launch, then is inflated and outfitted in Low Earth Orbit. Once inflated, the major diameter of the torus is 9.4 m and the minor diameter is 3 m for a total pressurized volume of 138 m^3. Specifications for the torus were determined from a preliminary layout of crew equipment, hardware, and passageways in the inflatable, and a 9.4 m diameter section provided the minimum acceptable cabin configuration. A detailed layout of the inflatable volume is found in the Human Factors & Habitability subsystem design section.

3.2 Subsystem Design

This section details designs chosen for the L_1 Gateway. The following systems comprise the sum of the spacecraft.

- Attitude Control System
- Avionics
- Electrical Power System
- Environmental Control and Life Support System
- EVA
- Human Factors and Habitability
- Propulsion
- Robotics
- Structures
- Thermal Control System

3.2.1 Attitude Control System

The L_1 Gateway attitude control system (ACS) is designed to stabilize and point the spacecraft in various orientations, or “attitudes”, desired by mission planners. In order to maintain its specified attitude, the system must reject disturbance torques produced by the environment in which it operates. External torques tend to rotate the spacecraft in the direction that they were applied, which is generally an undesired effect. These perturbations, if left unchecked, may jeopardize crew safety and mission success. For the L_1 Gateway, the ACS design selected utilizes a mechanical flywheel system to provide coupled attitude control and energy storage capabilities.

3.2.1.1 Functional Description

As previously discussed in the mission profile section, the L_1 Gateway will operate in four distinct environments: launch from Earth, Low Earth Orbit, transit from LEO to Lunar L_1, and on-station at Lunar L_1. Of these, the LEO and Lunar L_1 on-orbit phases present unique attitude control challenges for the L_1 Gateway.

During the Low Earth Orbit phase, the L_1 Gateway will be launched from Earth into a circular insertion orbit by an expendable launch vehicle. Once separated from the launch vehicle, the ACS will reorient the L_1 Gateway from an arbitrary post-injection attitude into a solar inertial attitude control mode. A solar inertial attitude is defined by the orientation of a spacecraft's coordinate system relative to its orbit. For this particular control mode, one axis of the spacecraft is fixed and pointed at the Sun while a second principal axis lying in the orbit plane points in the forward direction of travel. Figure 3.5 illustrates the solar inertial attitude control mode.

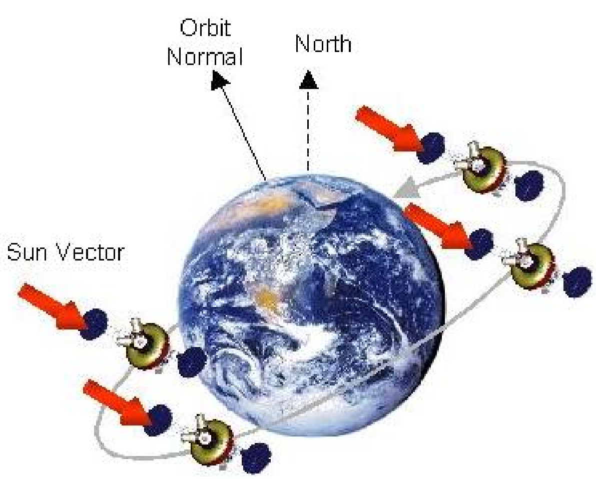


Figure 3.5 Solar Inertial Attitude

For the L_1 Gateway, a solar inertial attitude was chosen as it ensures the body-mounted thermal radiators will remain perpendicular, or "edge-on", to the Sun vector. In order to reject heat loads to its environment, a thermal radiator must point away from radiant energy sources such as the Sun, and this particular attitude ensures that for the Gateway. An edge-on radiator configuration allows the entire acreage to sink heat to deep space while not adversely collecting energy from the Sun. In addition to alleviating radiator operational concerns, a solar inertial attitude eliminates the need for active solar tracking by the photovoltaic arrays. The PV arrays will be initially deployed on-orbit and aligned with the solar-pointing spacecraft axis, ensuring constant unobstructed view of the Sun and eliminating the need for array repositioning. Thus, thermal radiator and PV array needs made a solar inertial attitude the optimal flight mode. Other considerations may also favor a solar inertial attitude, such as visiting vehicle docking operations, EVA activities, and window viewing, however these needs require further assessment.

Following completion of the planned Shuttle outfitting mission, the L_1 Gateway will be autonomously docked to the Solar Electric Propulsion Stage for transit to Lunar L_1. During this phase, attitude control will be provided by the SEP Stage. Upon undocking at the Lagrange point, the on-board ACS will once again orient the Gateway into a solar inertial attitude. This control mode, again selected for the reasons outlined above, will then be maintained for the 15-year operating lifetime on-orbit at Lunar L_1.

The second function of the Gateway ACS is to manage external disturbance torques while maintaining a desired attitude control mode. Factors that may perturb a spacecraft from its desired attitude include natural disturbances generated by interactions with its environment, and induced torques arising from nominal operation of the spacecraft. Each must be considered on its own basis to avoid unexpected behavior of the L_1 Gateway while in operation. It is the role of the attitude control system to counteract these perturbations.

Major sources of natural disturbances that must be considered for an ACS design are: spacecraft drag from atmospheric and solar pressure, gravity gradients across a spacecraft, and torques generated by interactions with Earth's magnetic field. For the Low Earth Orbit phase of the L_1 Gateway's mission, each is a significant source of disturbance torque and must be accounted. Once on-orbit at Lunar L_1, however, all but solar pressure become negligible. Gravity gradient torque is inversely proportional to the cube of the orbit radius and rapidly diminishes beyond LEO. Aerodynamic drag and magnetic field torques also become negligible, as the influence of these factors does not extend to the Lagrange points.

In addition to the environmental disturbances described above, design of the L_1 Gateway ACS must factor torques generated from nominal operation of the spacecraft. Though equally important as environmental torques, a detailed flight plan is needed to precisely quantify these perturbations. A few of the more significant known disturbances are docking and undocking of visiting vehicles, thruster firings for station-keeping, venting of consumables, crew movements in the pressurized volume, and operation of Gateway subsystems.

To provide a detailed design for the attitude control system, all disturbances acting on the spacecraft must be identified and accurately modeled. However, the depth of detail achieved in this study of the L_1 Gateway prohibited a thorough assessment due to uncertainties in the spacecraft mass properties data, incomplete operations plans, and other unknown factors. For the purposes of this design, an angular momentum storage capability of 1,000 N-m-s was adopted in lieu of a detailed requirement. This constraint was considered appropriate based upon similar spacecraft designs used in similar applications, though future studies of the L_1 Gateway should perform analyses to determine the precise attitude control requirements.

3.2.1.2 Trades Considered

For the L_1 Gateway ACS, three control methods were considered for selection: chemical reaction control system (RCS) thrusters, control-moment gyros (CMGs), and mechanical flywheels.

Chemical thrusters achieve attitude control by generating torque on a spacecraft with thruster firings offset from the center of gravity, thereby rotating the spacecraft. A chemical RCS is generally used in applications that require rapid slew maneuvers or have large stores of propellant on-board for other needs. However, a thruster system typically does not offer high pointing accuracy and requires consumable propellant, thereby increasing total system mass. Though a chemical RCS was selected to satisfy station-keeping requirements for the Gateway, the additional propellant cost of providing attitude control quickly became prohibitively expensive, far outweighing any synergistic benefits of using one common system.

In contrast to a chemical RCS, the control technique of CMGs and flywheels involves exchanging angular momentum between the system and the parent spacecraft. These systems offer high maneuverability and pointing accuracy, yet are more complex, thus more prone to failure. In addition, such devices may require momentum dumping to maintain the build-up of stored angular momentum within limits. However, specific attitude control requirements for the L_1 Gateway coupled with propellant mass savings integrated over its 15-year lifetime made momentum exchange systems more attractive than chemical RCS options. Potential momentum dumping requirements could be satisfied by the on-board station-keeping system.

Of the competing momentum exchange devices, a mechanical flywheel system was determined to hold several benefits over CMGs. Whereas CMGs require momentum dumping when the wheels reach their angular momentum storage capacity, flywheels can overcome this via power shuttering between the wheels, thereby eliminating any supplemental propellant requirements.[1] Furthermore, a single flywheel system can potentially be used for integrated attitude control and energy storage. By uniformly decreasing the rotational speed of the wheels, kinetic energy can be converted to electrical power, thus making flywheels an energy storage device. In combining these functions into a single system, significant mass savings are possible while providing redundancy to dedicated battery systems. For the reasons enumerated above, a mechanical flywheel system was selected to provide attitude control functions for the L_1 Gateway.

3.2.1.3 Reference Design Description

The mechanical flywheel concept selected for the Gateway is an integrated power and attitude control system (IPACS). As the flywheel system shares the energy storage burden with the primary batteries, this design has been sized to perform some marginal capability over the baseline momentum control needs. If an energy storage requirement did not exist for the ACS, there would be no additional capacity in the wheels, and they would be sized to their strength limits and momentum control requirements.

Attitude Control System	
Requirements	
Momentum Storage (N-m-s)	1,000
Energy Storage (W-hr)	20,000
System Specifications	
Mass (kg)	318
Volume (m^3)	0.288
Rotor Height (m)	0.209
Rotor Radius (m)	0.417

Table 3.3 Flywheel IPACS Concept

Specific requirements for the L_1 Gateway attitude control system are listed in Table 3.3 above. In addition to the aforementioned angular momentum storage requirement of 1,000 N-m-s, an energy storage capability of 20,000 W-hr will be provided. This represents a significant fraction of the overall energy storage need for the spacecraft. Sizing details for the 5-wheel flywheel IPACS concept are also given in the table. Currently, the ACS concept accounts for 2% of the overall L_1 Gateway inert mass. System resizing can be performed as more specific attitude control requirements become available.

The flywheel IPACS concept consists of five rotor wheels arranged in square pyramid formation, which is then packaged on the exterior of the L_1 Gateway. For placement constraints, the flywheel system "z-axis", the axis that intersects the base and apex of the square pyramid, must be aligned with a primary axis of its host spacecraft.[2] With regard to the present application, the z-axis has been aligned with the longitudinal axis of the L_1 Gateway. Other considerations with placement location were made. As the ACS stores energy and provides power to the spacecraft, the system has been packaged near other power system components to minimize transmission losses and employ existing thermal control capabilities. Figure 3.6 below illustrates packaging of the flywheel IPACS on the Gateway.

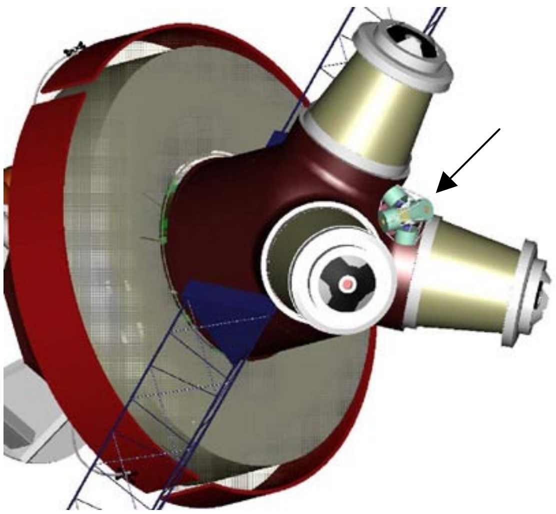


Figure 3.6 Gateway ACS Packaging

3.2.1.4 Technology Needs and Design Challenges

On-going technology efforts for the flywheel IPACS concept are concentrated on lightweight composite rotor development and high efficiency magnetic bearings. For the system, integrated power and attitude control has not yet been demonstrated on development hardware in a laboratory environment, though individual components have been tested. These technologies in the IPACS concept are currently estimated between technology readiness level (TRL) 3 and 5. However, as the L_1 Gateway is long-term application at least ten years from flight, a number of advanced technologies can be incorporated as they become available. Therefore, the overall flywheel system concept selected here was categorized as a TRL of three.

3.2.2 Avionics System

The avionics system for the Gateway provides for the command, control, communication, and computation required for the carrying out the mission from launch to operation at Lunar L_1. These provisions reside in the context of human flight-critical operations and, therefore, must meet the associated reliability requirements.

3.2.2.1 Functional Description

The primary function of the avionics system is to provide for control and monitoring of the Gateway by local and remote users. External commands received from crew input devices or remote sources are processed by avionics computers and then relayed to the appropriate system to actuate the command. In return, Gateway systems will provide health information to the avionics computer, which then projects this data to the user. Communication systems are provided by the avionics system to transmit data, voice, and video information within the Gateway, to visiting vehicles, and to Earth. The process of relaying information forms a feedback loop for command and control of the Gateway, with the avionics system at the center.

As the Gateway will be uninhabited for much of its lifetime, the avionics system must also support remote teleoperation of the Gateway from both Earth and visiting vehicles. This includes system startup, command, and health monitoring as crews approach from Earth and the lunar surface. To conserve resources, the Gateway will be placed in a stand-by mode when uninhabited, thus must be prepared for nominal operation prior to crew arrival.

In addition, it is the role of the avionics system to maintain an accurate navigation state vector, including position, velocity, and atti-

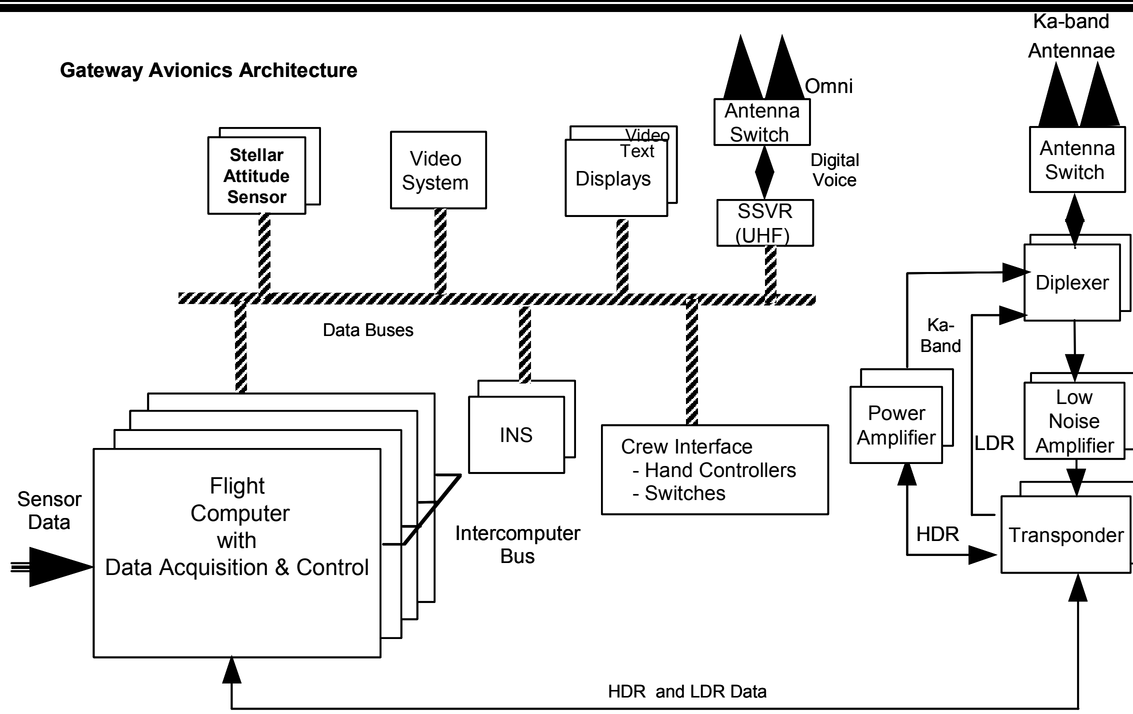


Figure 3.7 Gateway Avionics Architecture

tude. The navigation information is then processed and commands are sent to the propulsion system and ACS for maintaining position and attitude.

3.2.2.2 Trades Considered

No particular trades were considered for the initial design of the avionics system for the Gateway. The proposed avionics system was based on similarity to other mission critical systems under development such as the X-38 and other projects for improvements in avionics technology. This was considered adequate for the level of definition required for meeting the power and mass requirements in this iteration of the design. Future trade studies should be performed to analyze the optimal combination of advanced avionics technology, with a focus on reducing mass, power, and volume.

3.2.2.3 Reference Design Description

Figure 3.7 describes a high-level view of the Gateway avionics architecture. The heart of the avionics system is a set of flight computers which control all aspects of the flight from launch to on-orbit operation at LL_1. The computers are responsible for overall system management and producing caution & warning display information. The flight computer system is a quad-redundant system based on the X-38 Fault Tolerant Processor model and the Universal Mini-Controller under development by the Avionics division at NASA Johnson Space Center. The four computers are distributed throughout the Gateway to collect data from subsystems near their respective locations.

An Inertial Navigation System (INS) based on the ring laser gyro provides constant attitude information used by the flight computers in connection with long-range tracking to determine and maintain its inertial states and attitude knowledge. Initialization of the attitude is autonomously performed by a stellar attitude sensor. Attitude information, gathered by the INS and processed by the flight computers, is then sent to the ACS for physically maintaining attitude. Further information about this system is found in the attitude control section.

The Gateway avionics system must also support the rendezvous and docking of visiting vehicles. The Gateway will use passive laser retro-reflectors to provide targets for Laser Detection and Ranging (LADAR) systems. Active LADAR systems on other vehicles are used to determine range information for rendezvous operations and for fine range and relative attitude control during docking operations.

To enable remote operation of the Gateway from Earth and visiting vehicles, a system of Ka-band and UHF communication has been selected. The Ka-band system will provide for the high-rate transmission of data, voice, and video from the Gateway directly to Earth and for reception of command data from Earth. A UHF space-to-space radio system will support operations between all other vehicles.

The avionics video system will provide status views of various operational activities by the crew and possibly external views of other vehicles, the Moon, or Earth. Crew input devices, crew displays, and caution & warning panels will provide the appropriate interfaces as required for manual control by the crew. Finally, wiring for the avionics system is assumed a combination of fiber optics, wireless transmission, and parasitic use of the power buses where applicable. The wiring will be optimally selected to minimize mass and maximize reliability.

Physical attributes of the Gateway avionics system are summarized in Table 3.4.

Gateway Avionics		
Component	**Mass**	**Volume**
Attitude Initialization	6	0.005
Voice Peripherals	4	0.009
Communications	24	0.020
Video	8	0.005
Displays & Controls	14	0.011
DMS	35	0.503
Wiring	121	0.000
INS	39	0.046
Total	**251 kg**	**0.6 m^3**

Table 3.4 Avionics System Specifications

3.2.2.4 Technology Needs and Design Challenges

Current technologies used in avionics designs were considered adequate for meeting the guidelines of the Gateway avionics systems. These guidelines focus on meeting launch mass constraints to which the avionics system, even with current technology, contributes only a small portion. It would certainly be expected that, by the time of implementation, advances in avionics technology would provide additional power, mass, volume, and performance enhancements. The primary constraining factor to maintaining state-of-the-art technology is the requirement for radiation tolerance and electronic robustness of spaceflight-critical systems. The Gateway avionics system is considered to be at a TRL of six.

3.2.3 Electrical Power System

The proposed Electrical Power System (EPS) for the Gateway provides the user with 12 kW of nominal power and up to 14.4 kW peak power. Because of the wealth of information learned during the design of the CTV power system, similar architectures and technologies were incorporated in the Gateway. This approach allowed commonality of hardware across all vehicles.

3.2.3.1 Functional Description

The Gateway will be launched and injected to LEO by an expendable launch vehicle. While on the launch pad, power is assumed provided by ground support equipment through the launch vehicle. Three minutes before launch (pre-launch phase), this power is disconnected and the Gateway is assumed to survive on its own internal power during launch, ascent and orbit injection. The launch phase, lasting 7.8 minutes, will require 1.0 kW peak from the EPS.

Once in orbit, preparations will commence for jettison of the fairing enclosure and deployment of the Gateway. During the deployment and outfitting phases, it is estimated that the EPS system should provide 2.0 kW peak until rendezvous and docking with the SEP Stage. While in LEO, the Gateway must also store sufficient energy for the 35-minute eclipse periods that occur every orbit. Although the entire deployment phase of the Gateway may take up to twelve hours, deployment of the PV arrays should be completed within the first orbit (ninety minutes after orbit injection). Once the Gateway is docked to the SEP, power will be provided to the Gateway by the SEP power system.

Upon arrival at LL_1, the SEP will undock, release the Gateway, and return to Earth for reuse. The Gateway will then deploy its PV arrays. From separation to array deployment, a maximum time lap of about two hours could be expected, during which 2.2 kW peak power should be required. The Gateway will then begin its on-orbit lifetime and host missions, supplying power to its own systems and various visiting vehicles. During these phases, the Gateway EPS must provide a continuous 12.0 kW of power (14.4 kW peak), except during eclipse times in which only 7.0 kW for 13 hours (91 kW-hr) will be required. Further detail about the peak power and energy storage requirements is found in the Spacecraft Specifications section.

3.2.3.2 Trades Considered

Three primary trades were considered for the Gateway EPS. The first trade involved the configuration of the photovoltaic (PV) arrays used to provide primary power, with competing options being a set of inflatable, self-rigidifying arrays or mechanically deployed, retractable arrays. For the inflatable array option, two small arrays would be used to provide power in LEO. Upon docking with the SEP Stage, these arrays would be jettisoned, as they cannot be retracted. Once on-orbit at L_1, two larger arrays would then be inflated and rigidified for the remainder of the Gateway lifetime. In contrast, the retractable array concept consists of two large arrays that are deployed in LEO, retracted for the transfer to LL_1, and then redeployed after SEP undocking. For the Gateway EPS, it was decided that a set of two retractable PV arrays would be used. Though requiring slightly more mass than the inflatable arrays, this concept does not waste system resources by ejecting valuable PV arrays, rather retracts itself for later use. In addition, the CTV design utilizes retractable PV arrays for its EPS, therefore enabling technology commonality with the Gateway.

The next trade considered focused on energy storage options for the Gateway. As previously mentioned, the energy storage requirement for occultation periods is high (91 kW-hr), and a sizeable system will be required. High energy density Lithium-ion batteries have been identified as a promising solution to this problem, and are utilized in other elements of the Gateway Architecture, therefore will be used in the Gateway EPS.

However, a trade remained involving the form in which these batteries would be implemented. The traditional approach for batteries consists of building cylindrical or prismatic cell stacks to attain the desired output voltage. However, a revolutionary concept was considered which uses Li-ion batteries rolled into fibers. These fibers function identically to cell stacks but can also be integrated in a single-ply or weave pattern to provide reinforcement of walls, partitions, floors, or other common structures. Due to the tremendous potential mass savings from this concept, a fiber Lithium-ion battery system was chosen for energy storage.

Finally, the power management and distribution (PMAD) architecture of the Gateway EPS was considered. The first candidate was a 28-V_{DC} Electrical Power Control Unit (EPCU) system. Advantages of this approach were system simplicity and commonality with other Architecture elements, albeit at a significant mass and volume cost. As an alternative, a 400 Hz, 3-phase, 115-V_{AC} system was also considered. This system offers wiring mass reduction and the ability for crewmembers to use personal commercial off-the-shelf (COTS) items, a feature which should not be underemphasized. However, this architecture requires inverters to convert the direct current (DC) from PV arrays and batteries into alternating current (AC), as well as converters to provide the 28 V_{DC} required by visiting vehicles. Despite these additional complexities, the AC system was chosen for the Gateway EPS due to its overall mass savings, flexibility, COTS friendliness, and reduced operations and integration issues.

3.2.3.3 Reference Design Description

As mentioned, the power management and distribution system for the Gateway EPS (see Figure 3.8) is a 400 Hz, 3-phase, 115-

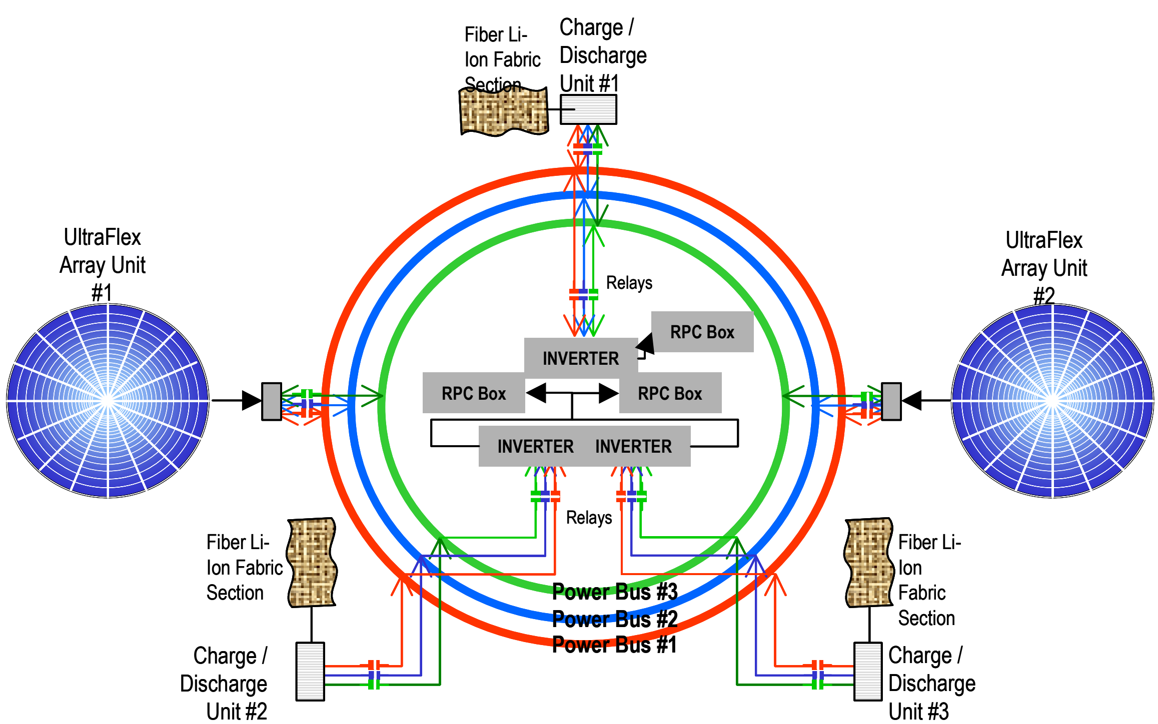


Figure 3.8 Gateway EPS Architecture

V_{AC} architecture with 3 power distribution systems. The primary distribution system consists of 155 V_{DC} power supplied by the PV arrays and fiber Li-ion batteries to a dual-redundant ring bus system. From the primary power buses, the secondary distribution system provides nine inverter boxes to convert the DC power to either 400 Hz, 3-phase, 115 V_{AC} or 400 Hz, single-phase, 110 V_{AC} power. This system then distributes the 115 V_{AC} power to the Gateway via twelve RPC boxes. Finally, tertiary power distribution is available to visiting vehicles and within the Gateway. A set of nine AC/DC converters are located near the docking ports to convert 115 V_{AC} power from the secondary distribution system to 28 V_{DC} as required by other elements in the Architecture. Frequency converters are also provided to convert the 400 Hz, 110 V_{AC} power to 60 Hz for use by COTS equipment. Interspersed throughout the Gateway PMAD are twenty-four relay boxes to close contact between the batteries, PV arrays, and inverters. A diagram of the system architecture is provided in Figure 3.9.

To provide 12 kW at LL_1, the PV arrays must produce 22.3 kW of power in order to compensate for losses in the PMAD system (70% efficiency) and an extra 30% for peaking. The PV array is assumed populated with Gallium Arsenide cells that yield an array efficiency of 21%. At a solar energy density of 1.4 kW/m^2, 76 m^2 of array will be required. For the Gateway, two circular retractable arrays are provided at 126.5 kg and 1.9 m^3 each. This includes the array, a container, the deployment mechanism, and array electronics. In addition, the PV array system provides a pair of retractable truss segments, truss containers, and articulating joints for solar tracking. A deployable truss is used to extend the PV arrays away from the Gateway core to enable articulation and avoid visiting vehicle interference issues.

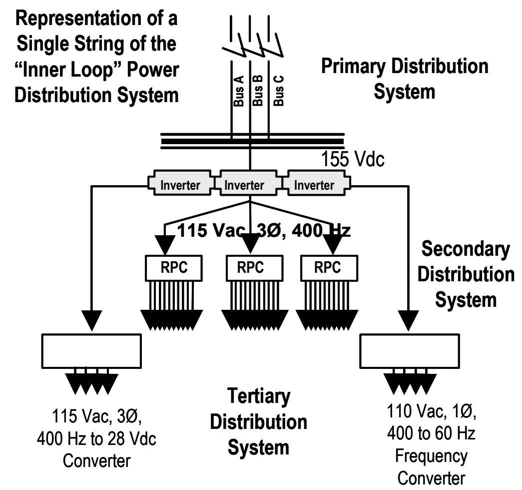


Figure 3.9 Power Distribution System

Although the Gateway will fly in a solar inertial attitude and not require active PV array solar tracking, some phases of the mission may require array gimbaling, therefore an articulating 2-degree-of-freedom joint has been provided. Once deployed, the truss system will occupy 40 kg and 12.5 m^3.

The energy storage requirements for the L_1 on-station phase of the mission were estimated to be about 91 kW-hr, of which 20 kW-hr will be satisfied by the Gateway flywheel attitude control system. The remaining 71 kW-hr represented a challenge since it might require 792 kg of thin-film Li-Ion battery at 200 W-hr/kg. In this particular case, it was estimated that the fiber Li-Ion battery system could yield up to 660 kg of fibers (assuming overall battery system mass of 792 kg for 71 kW-hrs). These fibers will be integrated into the inflatable structure of the Gateway as flooring members, wall partitions, etc. Also part of the energy storage system are three battery charge/discharge units at 20 kg and 0.036 m^3 each.

The Gateway EPS wiring harness consists of 3 main bus cables, 24 jumper cables, 816 secondary power distribution cables, and wiring harness secondary structure. The three main buses are rated at 155 V_{DC} for power generation and distribute 12 kW, 115 V_{AC} power to the user. Each 1/0-AWG ring bus cable is 20 m long at a linear density of 0.2 kg/m. The 10-m jumper cables are assumed the same construction as the primary bus cables, and are used to connect the arrays, batteries, and inverters to the primary bus. For the secondary distribution system, 816 10-m cables are required for the RPC boxes at 68 cables per box. This cable is a twisted-pair, jacketed, 26-AWG assembly with a linear mass density of 0.0042 kg/m. Finally, 20% has been added to the mass and volume of the wiring harness to account for secondary structures such as cable ties, junction boxes, and production breaks.

Physical attributes of the overall Gateway EPS are summarized in Table 3.5.

3.2.3.4 Technology Needs and Design Challenges

Though a potentially revolutionary concept in spacecraft power systems, several unresolved issues remain with the fiber Li-ion battery concept. A better understanding of how the energy densities of the Li-ion battery extrapolate from a thin-film to a fiber structure is needed. Interconnectivity of thousands or perhaps millions of fibers is also an issue. Future iterations of the Gateway EPS design should perform a full assessment of the fiber Li-ion battery capability and integration into the spacecraft structure. Currently, this technology is only at TRL 2, although it is being funded by DARPA to further its development into a commercial product as well as for military applications.

Gateway EPS			
Component	**Mass**	**Volume**	**TRL**
PV Arrays	253	3.812	7
Deployment Truss	40	12.348	6
Battery	192	0.174	2
Wiring Harness	243	10.145	9
PMAD	607	0.979	6
Total	**1,335 kg**	**27.5 m^3**	

Table 3.5 EPS Specifications

Further work is required to develop a more accurate conceptual design of a 115 V_{AC}, 3-phase, 400 Hz remote power controller (RPC) box. Present designs are at a purely conceptual stage.

PV arrays similar to those selected for the Gateway EPS have been tested in a laboratory environment, and are considered at a TRL of six. Advances in photovoltaic cell technology may be implemented as they become available.

3.2.4 Environmental Control and Life Support System

The environmental control and life support system (ECLSS) provides essential functions to support life and maintain a safe, habitable environment for the crew. This includes providing breathable air and water to the crew, managing waste, and controlling the internal atmosphere. To reduce the amount of crew consumables needed for long-duration spaceflight, and as a result, initial launch mass, efforts in ECLSS designs are focused on “closing the loop”. This philosophy entails recycling valuable resources such as air, water, and human waste rather than discarding after a single use. To maintain launch needs within reason, closed-loop life support systems are an enabling technology for future human exploration beyond Earth’s Neighborhood. As a primary design goal of the Gateway is to demonstrate such enabling technologies where prudent, closed-loop systems have been selected for this application.

3.2.4.1 Functional Description

Functions to be provided by the ECLSS include atmosphere control and supply, atmosphere revitalization, temperature and humidity control, fire detection and suppression, water management, and waste handling. A design goal of the ECLSS, and the Gateway as a whole, is to be used as testbed for advanced technologies. This decision will have a major impact on the types of systems selected to provide the functions above.

As levied by the top-level requirements, the ECLSS must support a crew of four performing four missions per year at the Gateway. Architecture groundrules baseline two of these missions to be lunar surface expeditions, and the other two as telescope assembly and servicing missions. For each lunar mission, the ECLSS will assume the crew will spend twenty-five days in the Gateway and thirty days for telescope-related missions. This estimate is somewhat conservative, yet adds a margin of safety to the ECLSS design. As previously discussed, the Gateway has been assumed at a 2-year resupply frequency, though this decision is open for future trade.

Initial pressurization of the Gateway following launch will be provided by the ECLSS, with a total pressurized volume of 275 m^3 required. The Gateway will remain pressurized for its entire 15-year lifetime. It was assumed that no additional repressurization capability would be required, and in the event of an emergency depressurization, the crew would transfer to the CTV and return to Earth. Crew needs from the ECLSS amount to 0.84 kg of oxygen per person-day, an ISS-class water allotment (2.8 kg/person/day) for food rehydration and drinking water, and 6.8 kg/person/day for hygiene water. Each crewmember will produce 1 kg of carbon dioxide per day.

Additional needs from the ECLSS are to support nominal EVA activity. A 3.68 m^3 airlock will be cycled eighty-four times per resupply period, with 15% airlock atmosphere loss (0.42 kg) per cycle. The system must also provide space suit umbilical support for four crewmembers with cooling water.

3.2.4.2 Trades Considered

Several trades were considered for the Gateway ECLSS design. The first trade involved the method of storing nitrogen (N_2) and oxygen (O_2) used for cabin atmosphere, with the competing options being high-pressure gas or cryogenic liquid storage. High-pressure gas storage with composite material tanks is competitive against cryogenic storage in mass, though cryogenic storage offers some advantage in volume savings. However, significant power consumption is required when liquid oxygen and nitrogen are used to quickly pressurize the Gateway. Cryogenic oxygen is already required for the propulsion station-keeping system, thus mass savings were possible by utilizing this resource. Therefore, an optimal combination of high-pressure and cryogenic atmosphere storage systems have been selected for the ECLSS. Gaseous O_2 is used for pressurizing the inflatable Gateway cabin, and for all other needs, cryogenic oxygen is drawn from the propulsion system. Nitrogen is stored as a high-pressure gas for all applications.

The next trade involved the various technologies available for carbon dioxide (CO_2) removal. The competing options were four-bed molecular sieve (4BMS) CO_2 removal technology or solid amine removal. A 4BMS system is a more developed technology, as a closed air revitalization system including a 4BMS, an oxygen generation system, and a Sabatier CO_2 reduction system is being developed for the International Space Station. Additional development work would be required to integrate a solid amine CO_2 recovery system into a closed atmosphere recovery system (ARS). Therefore, the four-bed molecular sieve technology has been selected for Gateway carbon dioxide removal and recovery, and is integrated with an oxygen generation system and a Sabatier CO_2 reduction system for a complete ARS.

For the water management system, three candidate technologies were considered: Biological Water Recovery System (BWRS), Vapor Phase Catalytic Ammonia Removal (VPCAR), and the ISS Water Processor (WP). The substantial mass penalty of hardware and required resupply is a major disadvantage of the ISS Water Processor, so it was eliminated from consideration. The advantages of BWRS are low power consumption, mass, and resupply needs as compared to VPCAR. However, it requires longer turnaround and restart time relative to VPCAR, and meeting the requirement of uninterrupted nutrition feed to the bioreactor microorganisms when the Gateway is not staffed was a major concern. The Gateway will be uninhabited for much

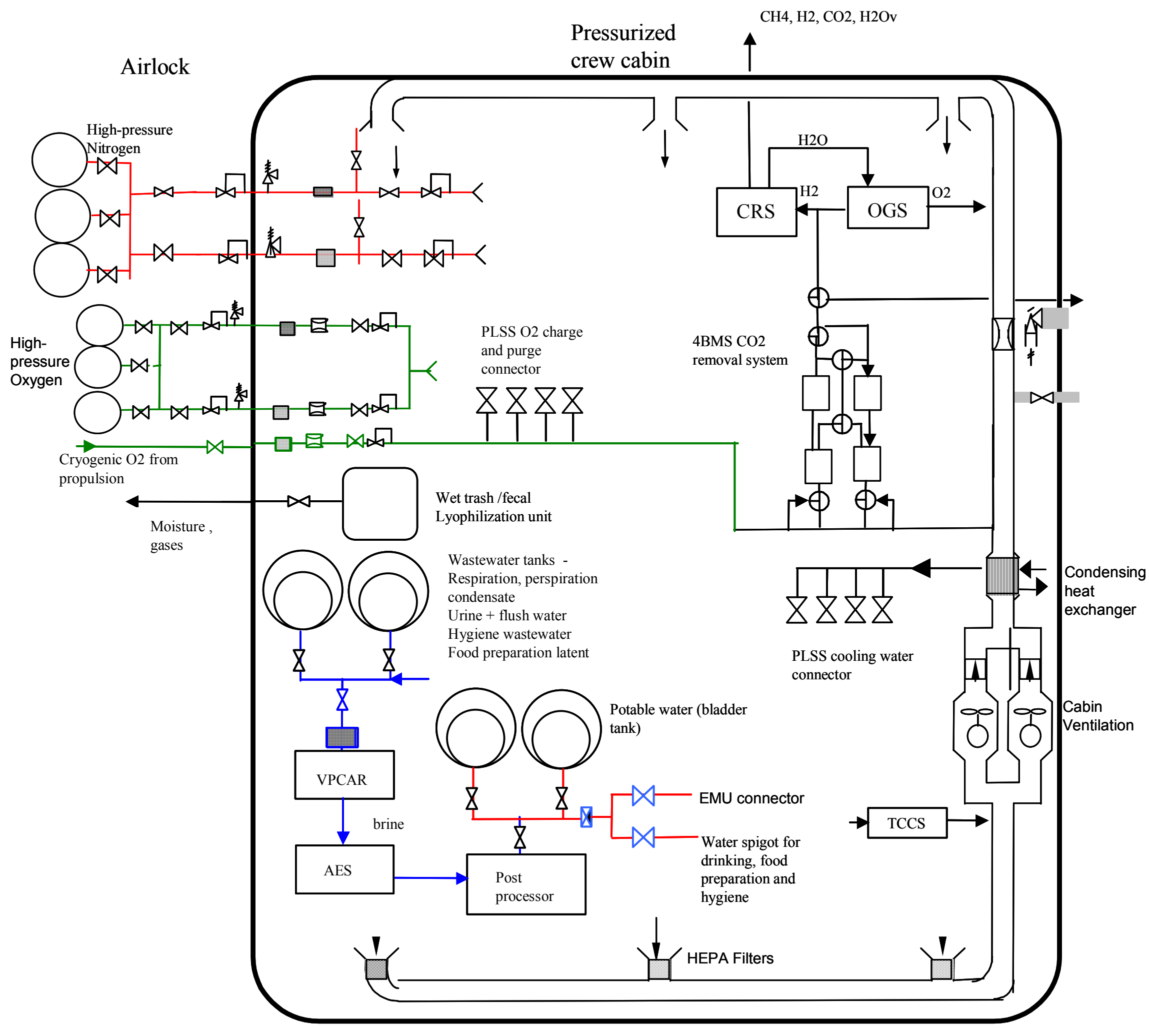


Figure 3.10 Gateway ECLSS Schematic

of its 15-year lifetime, thus the biological water recovery system was less attractive. Advantages of VPCAR are low mass, volume, and rapid turnaround. Though requiring greater power consumption, this was less of a concern as the Gateway is considered power-rich. For the reasons enumerated above, Vapor Phase Catalytic Ammonia Removal was selected as the Gateway water recovery system technology.

3.2.4.3 Reference Design Description

The reference ECLSS design for the Gateway is shown schematically in Figure 3.10 and described in Table 3.6. The internal atmosphere operating pressure was selected at 62 kPa (9.0 psia) primarily to reduce nitrogen and oxygen repressurization requirements, reduce atmosphere leak to space, and to minimize EVA pre-breathing time required. Additional structural benefits may be derived. This pressure is equivalent to the atmosphere pressure in Denver, therefore should be acceptable for human spaceflight. The oxygen-enriched cabin atmosphere of 70% nitrogen and 30% oxygen also maintains material flammability limits within the range currently tested and approved for spaceflight. As a comparison, the Apollo Lunar and Command Modules used reduced-pressure, pure oxygen atmospheres. A mixed cabin atmosphere, the need to provide umbilical support to the suited crew, and the desire to have closed air and water systems in the Gateway drove design of the ECLSS system.

As traded, high-pressure, 30-MPa oxygen (4,350 psia) is used for Gateway pressurization. The high-pressure oxygen tanks will be stored in the airlock, while the cryogenic O_2 tanks will be packaged on the exterior of the vehicle. Cryogenic liquid oxygen provided by the propulsion system is selected for crew metabolic use, leakage make-up, spacesuit purge, and umbilical support. The Gateway propulsion system will provide 491 kg of liquid oxygen per 2-year resupply. High-pressure 30-MPa nitrogen is also stored in the airlock and is used for airlock repressurization, make-up for leakage, and pressurization of potable water and waste-water storage tanks. When the Gateway is not staffed with crew, the cabin pressure will be in an uncontrolled but monitored state to conserve resources. However, cabin ambient temperature will be controlled within an appropriate range to ensure function of Gateway systems. Prior to crew ingress from the CTV, cabin pressure, atmosphere composition, temperature, and humidity will be controlled to appropriate conditions.

Cabin ventilation and atmosphere revitalization is provided through an air recirculation loop and has the following functions: cabin air recirculation, filtration, temperature control, CO_2 removal, and trace contaminant control. A condensing heat exchanger is used to control cabin ambient temperature and atmospheric humidity. As mentioned in the trades section, a four-bed molecular sieve carbon dioxide removal system is used to maintain CO_2 within an appropriate concentration range in the pressurized volume, and to recover CO_2 for further processing. An Oxygen Generation System (OGS) employing water electrolysis technology is used to provide oxygen for crew metabolic consumption. Another product generated from the OGS, hydrogen, will react with CO_2 recovered from the 4BMS and yield water as a product. This water will be recycled to the OGS as reactant. Thus, a closed air recovery system is used in the Gateway ECLSS.

A suit loop provides CO_2 removal, trace contaminant control, and humidity control during umbilical operations. The suit loop is purged with oxygen during the pre-EVA space suit purge and remains pressurized

Function/Subfunction	Technology
Atmosphere Control and Supply	
oxygen storage	high pressure for Gateway initial pressurization and cryogenic storage for other usages
nitrogen storage	high pressure storage
atmosphere pressure control	software operated (X-38) + regulators[1]
atmosphere pressure monitoring	high accuracy (ISS) pressure sensors
Atmosphere Revitalization	
carbon dioxide removal	four-bed molecular sieve CO2 removal (ISS)[2]
carbon dioxide reduction	Sabatier CO2 reduction
oxygen generation	water electrolysis (ISS)
trace contaminant control	fixed charcoal bed + catalytic oxidizer assembly + post-sorbent bed (ISS)
atmosphere composition monitoring	major component only (ISS) monitors
Temperature and Humidity Control	
cabin ventilation	ducting and blowers
temperature and humidity control	condensing heat exchanger (accounted for in TCS)
atmosphere humidity control	condensing heat exchanger
particulate and microbe control	high efficiency particulate air (HEPA) filters
Fire Detection and Suppression	
fire detection and suppression	smoke detector/halon
Water Recovery and Management	
potable water storage	bladder tanks
water microbial control	iodine microbial check valve
water quality monitoring	Process Control Water Quality Monitor, PCWQM (ISS)
urine, flush water storage	16-hour storage, stored and stabilized in refrigerator, then processed by the VPCAR
wastewater storage	16-hour storage, stored and processed by the VPCAR
brine storage	bladder tanks combined with condensate storage
wastewater processing	Vapor Phase Catalytic Ammonia Removal (VPCAR) + Air Evaporation System (AES)
post processor	Ion-exchange beds
Waste Management	
urine collection	Provided by the crew accommodation
feces collection and storage	Provided by the crew accommodation
solid waste processing and storage	Lyophilization process to be used for human solid wastes and diapers for water removal. The dried solid waste will be bagged and stored for disposal on Lunar surface.

[1]Primary pressure control by regulators during cabin repressurization.
[2]ISS Carbon Dioxide Removal Assembly (CDRA) and CO2 vacuum pump/compressor currently under development.

Table 3.6 ECLSS Reference Design Description

with 100% oxygen (at the spacesuit pressure) when the airlock is depressurized. The purged oxygen may be pumped back into the cabin or released to space, all while maintaining the maximum oxygen concentration inside the cabin below 30%.

For Gateway water needs, a 3-day supply of potable water is stored for crew drinking, food rehydration, and hygiene. This supply will provide the crew sufficient water before enough wastewater has been collected for regeneration. Vapor Phase Ammonia Catalytic Removal (VPCAR) technology is used to recovery 98% of the potable water from the wastewater. The remaining 2% brine of VPCAR will be reprocessed in the Air Evaporation System (AES) to recover water. A post-processor will be used to process water produced from the AES and ensure the water meets potable quality. Overall, there will be a net water surplus from the Gateway closed wastewater recovery system. Condensate from the condensing heat exchanger, hygiene water, urine, and its flush water will be collected in a bladder wastewater storage tank for processing in the VPCAR system.

Finally, human solid waste will be collected in the commode and from EVA operations (diapers), then processed in lyophilization units to remove moisture. The dried solid waste will be bagged and stored for disposal. The issue of trash removal from the Gateway is an item for future study. See Table 3.7 for a summation of the Gateway environmental control and life support system.

Gateway ECLSS			
Component	Mass	Volume	TRL
Atmosphere Control	660	2.290	4
Atmosphere Revitalization	1013	2.857	4
Temperature Control	88	6.280	6
Fire Detection	22	0.054	9
Water Management	1027	4.165	6
Waste	42	0.226	3
Total	**2,852 kg**	**15.9 m^3**	

Table 3.7 ECLSS Specifications

3.2.4.4 Technology Needs and Design Challenges

To minimize resupply requirements, closed air and water recovery systems were designed for the Gateway ECLSS. Many of the challenging technologies selected for the air revitalization system (ARS) and water recovery system (WRS) are still in the development stage. These technologies include carbon dioxide removal, Sabatier CO_2 reduction, oxygen generation, Vapor Phase Catalytic Ammonia Removal, and lyophilization technology.

Though a carbon dioxide removal assembly (CDRA) is currently being used on ISS (TRL 9), collected CO_2 is dumped overboard rather than reprocessed. To recover CO_2, a carbon dioxide vacuum compressor needs to be developed, and compressor development is estimated at a TRL of three. The Sabatier CO_2 reduction and oxygen generation water electrolysis has been used on the Lunar-Mars Life Support Test Project (LMLSTP) 90-day test, and are both considered TRL 6.

A breadboard VPCAR system has been tested, however, the technologies for processing NO_X and SO_X generated from the catalytic oxidation reactors need to be developed and verified. A low-noise, long-duration compressor for low temperature evaporation and compression of water vapor also needs to be developed. The overall TRL for VPCAR is estimated at four.

Lyophilization technology, or freeze-drying, was selected for remove moisture from human solid waste, diapers, and other waste products. A breadboard unit to demonstrate this technology has been tested (TRL 3), though further development work is required.

3.2.5 EVA System

To aid in the assembly and servicing of gossamer telescopes at Lunar L_1, the Gateway must provide a robust system for routine EVA capability. Though robotic partners may assist, certain complex, non-linear assembly tasks are best suited for human interaction, thus requiring EVA crew. Due to their complexity, a number of sorties will be required per telescope construction mission. In addition, EVA crew will be required for the maintenance of the Gateway over its 15-year lifetime.

3.2.5.1 Functional Description

The Gateway EVA system is designed for ten 2-person EVA days per telescope mission and one day per year for Gateway maintenance. As the baseline resupply schedule is set at two years, and two telescope assembly missions are planned per year, forty-two EVA days will occur per resupply. All EVA days are sized for an eight hour duration, but are actually accomplished with a portable life support system (PLSS) that is sized for four hours. Consequently, there are two airlock cycles per EVA day, and eighty-four cycles between resupply.

Also required of the system is a dedicated airlock to support nominal, frequent EVA, umbilical support, and a PLSS-recharge system. EVA toolboxes and a work platform are provided for the telescope assembly area. Translation aids are provided to enable crew mobility around the vehicle and SAFER emergency translation aids are available in the event a crewmember becomes untethered from the Gateway.

The space suits for each mission are brought into the Gateway from the Crew Transfer Vehicle (CTV). Each suit is customized to the particular crewmember performing the mission, therefore a set of reusable suits will not be provided at the Gateway. However, EVA system spares for individual components are provided.

3.2.5.2 Trades Considered

The major trade for the Gateway EVA system centered on space suit recharge, a challenge experienced with other elements in the Gateway Architecture. The suit oxygen system requires 3000-psi gas, however the spacecraft reservoir provides 250-psi liquid oxygen. The recharge system trade options consisted of either providing a dedicated, 3000-psi source for EVA use, or using the liquid oxygen tank and performing thermal pressurization and compression. It was determined that a shared liquid oxygen tank with ECLSS and propulsion would result in mass savings over a dedicated high-pressure gas source.

3.2.5.3 Reference Design Description

Across the Gateway Architecture, a single space suit design will be used to handle both lunar surface exploration and zero-g operation. The space suits were specifically selected to gain operational experience, and the PLSS schematic chosen is a system designed for use on Mars. A key to this design involves a carbon dioxide and humidity removal system that has two noteworthy features. First, to avoid replacing a CO_2 absorption canister while on EVA to accomplish a space suit recharge, the design is a swing bed system that is not time limited. This condition may occur due to the need to walk back from a long distance expedition after rover failure. Secondly, the system can be made to reject CO_2 from the suit to the CO_2-rich environment of Mars (i.e. against a partial pressure gradient).

The other major technologies included in the space suit include a radiator topped by a membrane water boiler for heat rejection. The PLSS also provides a provision for EVA crew heating as well as cooling since the thermal environment between shadow

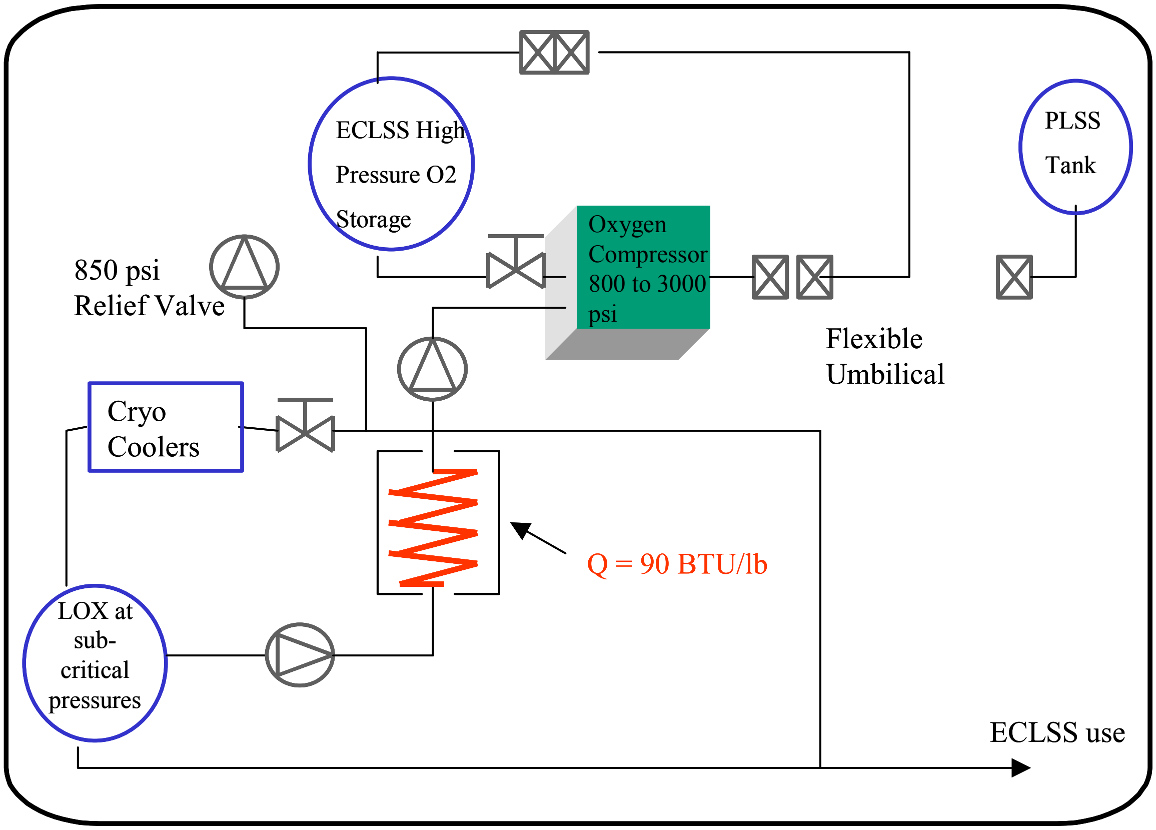


Figure 3.11 Space Suit Recharge Schematic

and sunlight fluctuates greatly on the lunar surface and in deep space. Crewperson heating is needed on Mars, which has a biased cold environment. The space suit mobility garment is a back-entry suit with mobility designed for surface exploration. This means the mobility is present to allow the crewmember to collect rock samples, deploy scientific instruments, and move about the surface easily, however this type of mobility may be equally important in zero-g at the Gateway. The suit and PLSS are designed to be repairable by the crew during the mission, which requires a modular architecture.

The PLSS recharge system provides thermal pressurization and phase change of the oxygen from 250 psi to 800 psi, and compression by an oxygen recharge compression assembly (ORCA) to 3000 psi. Since the ORCA cannot accept gas inlets less than approximately 800 psi, the ECLSS oxygen tank to provide emergency pressurization is used as a source when the liquid supplied source drops below acceptable ORCA inlet pressures. After the PLSS units are refilled, the ORCA is used to pressurize the ECLSS emergency tank to 3000 psi. A schematic of the space suit oxygen recharge system is depicted in Figure 3.11.

Included in the airlock arrangement is a single flexible airlock that allows two persons to enter the Gateway at one time. The flexible airlocks configured as docking ports provide redundant entry and exit points. A gas-saving system will reduce consumables lost during an airlock cycle by recovering 85% of the airlock atmosphere. The gas-saving feature works as follows. During nominal two-person operation, the airlock starts at the cabin pressure of 62.0 kPa. The EVA crewmembers enter the airlock in their suits and close the hatch to the cabin. Gas is then pumped from the airlock back into the cabin, stopping at 6.9 kPa. The crew then bleeds the remaining atmosphere to the external vacuum and goes EVA. Upon return, the crew enters the depressurized airlock, closes the door, and then equalizes the airlock with the cabin atmosphere. This operation saves 3.9 kg of atmosphere per airlock cycle at the cost of 1.4 kW of power during the pumping cycle (25 minutes). The net loss of gas to the vacuum during an airlock cycle is 0.43 kg. In addition to conserving consumables and "closing the loop" for the Gateway, recovering airlock atmosphere will reduce contamination concerns during telescope assembly operations.

A staging area by the inside airlock hatch is included in the concept. This area provides volume to store all four space suits as well as suit spares and expendables. Provisions for suit donning, expendables recharge, and checkout are included. Any repair of the space suit is accomplished in this area as well. An unpressurized area by the outside airlock hatch is also included in the concept. It provides a location for EVA tool storage and allows handling of large objects that are to be assembled. Further definition of the work platform can be provided with detailed telescope assembly requirements.

EVA system spares to support the four suits and airlock suit recharge provisions are stowed in the Gateway EVA staging area until needed. The EVA tools provided consist of two external toolboxes containing mechanical and electrical equipment, and storage/tie downs. The tools are stowed in the unpressurized area just outside the airlocks. Once again, the exact suite of tools required may be defined by examining the telescope assembly tasks, however that information was unavailable for this iteration of the Gateway study. A generic set of commonly used equipment has been included as a placeholder.

Gateway EVA			
Component	**Mass**	**Volume**	**TRL**
Space Suits	926	5.670	3
Vehicle Support	212	0.340	3
EVA Translation Aids	123	3.360	9
EVA Tools	132	0.200	9
Airlock	433	8.180	3
Total	**1,826 kg**	**17.8 m^3**	

Table 3.8 EVA System Specifications

Specifications of the EVA system are summarized in Table 3.8.

3.2.5.4 Technology Needs and Design Challenges

Airlock system items that need technology improvement include the oxygen recharge system at TRL 3, and the soft, flexible structure, also estimated at TRL 3.

Technology needs are significant for the space suit. The CO_2 subsystem described is currently at a TRL of three. A thermal radiator small and lightweight enough to be used on the PLSS and the water boiler topping-unit is considered TRL 3. Packaging of the PLSS in the modular arrangement needed is at TRL 2. The suit garment to provide the mobility needed is at TRL 4. However, both the PLSS and suit are currently far too heavy for Mars. Lunar use will be affected by the weight as well. Technology development efforts for weight reduction are currently between TRL 1 and 2. High density, high cycle life power systems such as batteries or fuel cells are needed. Current power systems technologies needed to meet the lightweight criteria are at TRL 2-3.

Another significant obstacle in the technology is insulation (TRL 2) that will work in the pressurized environment of Mars. Current insulation depends on a vacuum environment. Though the lunar surface and Gateway do provide a vacuum environment, the need to get operational data on the insulation layer is pressing. The suit layer interacts most strongly with the dust and dirt of surface exploration.

Lightweight information management systems to provide the data rates needed and provide location information are at a TRL of one. Crewmember/robotic interfaces, which must be implemented as part of the information management systems, are at TRL 2-3.

3.2.6 Human Factors and Habitability

The goal of the human factors and habitability (HF&H) was to design a safe and habitable environment for the crew in the L_1 Gateway. A large part of this process was creating a pressurized volume for the crew where the functions of eating, sleeping, hygiene, exercise, and crew operations can be successfully carried out. Also included in this design are the subsystems of stowage, waste management, and the crew health care system.

3.2.6.1 Functional Description

A human-rated space system is one that "incorporates those designs features, operational procedures, and requirements necessary to accommodate human participants. This provides the capability to safely conduct manned operations, including safe recovery from any credible emergency situation."[3] The designs "are focused on system reliability, human-machine interaction, crew escape, and dealing with the consequences of the inevitable hardware and human failure."[4]

In designing the Gateway, the station was sized for a crew of four and a mission architecture based on both a lunar landing mission and a telescope-building mission. For the lunar landing mission, a crew time of 12 days was assumed. For a telescope-building mission, a crew time of 25 days was assumed.

Habitable volume for the Gateway was dictated by the necessary volume for the functions that needed to be accommodated within the station. Because the Gateway was designed to be an "oasis" for the crew after spending time on the CTV, requirements were based on the volumes necessary for each function to have a unique location on the Gateway. This design layout will prevent "hot-bunking" of crew functions. The minimum requirements for volume set for the Gateway were 60 m^3 of habitable volume and 150 m^3 pressurized volume. This is greater than the minimum required volumes for crewmembers to live for 12 or 25 days, which are 15.86 m^3 and 16.99 m^3 respectively, but accommodates the goal of the Gateway serving as a crew "oasis".

The primary crew functions that the Gateway is to accommodate are: sleeping/rest, privacy for clothing change, hygiene and waste collection, medical care, exercise, food preparation and consumption, crew restraint and mobility, operations, and maintenance and trash. For crew sleep, the Gateway shall provide a minimum volume of 1.50 m3/person. In addition, the Gateway shall provide 0.63 m3/person for stowage of operational and personal equipment.[5] For changing of clothing, the Gateway station shall provide a minimum volume of 0.88 m^3 with the dimensions of at least 172 x 72 x 71 cm.[6] To accommodate hygiene and waste collection, the Gateway shall provide a full-body cleansing unit which accommodates washing of all body areas, as well as oral hygiene, grooming, and shaving. In addition, this facility shall accommodate the collection and management of body waste.

The medical facility on-board the Gateway shall provide preventative, diagnostic, and therapeutic medical capabilities, as well as meet requirements in NASA-STD-3000, 10.9.3. The medical facility shall also provide privacy for the crewmembers for medical conferences to the ground. The exercise facility on the Gateway shall comply with NASA-STD-3000, 10.8.3.1, and should be located away from eating facilities for sanitation reasons. The crew galley and wardroom table used for food preparation and consumption should be collocated, and meet requirements specified in NASA-STD-3000, 10.5. Restraints and mobility aids shall be provided in the habitable volume of the Gateway for restraint of crewmembers, food, utensils, cooking equipments, and other loose crew equipment as specified in NASA-STD-3000, 11.7 and 11.8. Vehicle control/monitoring and science workstations shall be provided on the Gateway, and each crew station shall have a local vertical so that the vertical within a specific work station or activity center shall remain consistent, as specified in NASA-STD-3000, 8.4.3. Trash handling equipment and maintenance equipment shall be provided for all necessary functions in the Gateway.

3.2.6.2 Trades Considered

The primary trades considered by the HF&H team were:

- Crew quarters as private or dorm-style sleeping facilities
- Plumbed or unplumbed waste collection facility
- Partial-body or full-body cleansing hygiene system
- Medical facility level of support
- Types of exercise for which equipment will be provided
- Type of food to be provided for the crewmembers

Consideration was given to the operational scenario of the two possible missions, specifically that the crew would arrive at the Gateway via the CTV, which is not heavily outfitted with crew accommodations because of mass and volume limits. The concept of the Gateway is to be an “oasis” for the crew, and this operational assumption was considered when trades were evaluated.

For the crew quarters, a trade was evaluated between providing private quarters for each crewmember and providing a “dorm-style” sleeping compartment. Volume was the primary driver for this decision because mass and power were not significantly different for the two options. Because the psychological benefits of a private crew quarter location were determined to be significant, while the volume increase was minimal for the Gateway, private crew quarters were selected.

Three types of body waste collection facilities were considered for the Gateway: a “bags-only” system similar to Apollo, an unplumbed facility, and a plumbed facility. The “bags-only” system was eliminated quickly from the analysis because of psychological and sanitation/safety concerns with this method. For the unplumbed facility, a “Mir-style” commode was considered. This design provides a somewhat “Earth-like” facility to collect waste via a commode, but the waste containment is done through bags attached to the commode, which have to be changed regularly. This open-loop system provides no reuse of water through urine and fecal dehydration. The third option considered, the plumbed facility, is very similar to the waste collection system used on ISS. This would provide for the highest level of crew sanitation because of the minimal contact with urine, fecal matter, and emesis. In addition, this provides for the opportunity for a semi-closed loop or fully closed loop (depending on current technology at the time of fabrication) for water and waste. This is a benefit to the ECLSS, and the Gateway as a whole. Based on this evaluation, a plumbed facility for body waste collection was chosen.

Personal hygiene is considered very important for crew health, as well as morale and productivity. For hygiene, the options of a partial-body cleansing system and full-body cleansing system were considered. For the partial body cleansing capability, the crew would be provided with a water spigot and washcloths, as well as hygiene wipes. This would be a hygiene system similar to that currently baselined for ISS. For the full-body cleansing capability, the crew would be provided with a system that would allow for full-body cleaning similar to a ground-based shower. Technology for this system still needs to be developed, but after a close comparison, it was decided that the full-body cleansing capability would be important in reaching the goal of the Gateway serving as an "oasis" for the crew.

For a medical facility, three options were considered: a medical kit only, life support equipment for a nominal mission scenario, and life support equipment for a contingency mission scenario. Because the stay on the Gateway would be an absolute minimum of 12 days nominally, and the crew would arrive to the Gateway from the CTV (which has limited medical capabilities), the option of a medical kit only was eliminated. If an emergency occurred between ISS and the Gateway on the CTV, the Gateway would need to provide the capability to handle this when the crew arrived. Based on the assumption that the Gateway would be the oasis for the crew between missions on the CTV and a Lunar Lander, the third option was chosen. A full medical capability, including life support equipment necessary including life support equipment necessary for a longer duration stay due to contingencies, was deemed critical.

With regard to exercise, four options were considered: no exercise capability, limited resistive exercise, cardiovascular exercise only, and a combination of cardiovascular and resistive exercise capability. Due to the duration of crew stay on the Gateway and their inability to perform significant exercise on the CTV or Lander, the "no exercise capability" and limited resistive exercise option were eliminated from consideration. Because of the previously mentioned operational constraints, it was determined that both resistive and cardiovascular exercise would be needed on the Gateway. Any trip to the Gateway requires crewmembers to be away from Earth for a considerable amount of time, so it is critical to provide capability for them to maintain muscle mass (resistive exercise), as well as good heart health and bone density (cardiovascular exercise).

Both shelf-stable and conditioned (refrigerated/frozen) food was considered for the Gateway crew nutrition. Shelf-stable food would include rehydratable, thermostabilized, irradiated, and natural-form foods, similar to the food system on Shuttle. This would require a rehydrator and food warmer for food preparation. Conditioned food would include both refrigerated and frozen food, and would require both a refrigerator/freezer, as well as an oven with increased heating capacity compared to the food warmer. Although conditioned food was considered better for the crew from both a psychological and nutritional aspect, the mass, volume, and power required for providing both refrigerator/freezers and ovens on the Gateway precluded this from being considered seriously. The resupply scenario for the Gateway is such that a large quantity of refrigerator/freezers would be required to be at the Gateway and powered at all times.

Function	Technology
Sleep Accommodations	
Bunks	Shuttle sleep restraints
Privacy	Retractable cloth dividers
Waste Management	
Urine collection	ISS-style commode
Feces collection and storage	ISS-style commode
Solid waste processing and storage	Plumbed facility integrated with the ECLSS water system (based on ISS W&HC system)
Exercise	
Resistive training	TBD
Food Supply	
Food supply	Packaged Shuttle-type food system
Food preparation	Food warmer and food rehydrator (used on Shuttle)
Stowage	
Containers	ISS soft stowage bags
Racks	Simplified ISS soft stowage racks
Lighting	
General lighting	Solid-state (LED) lights
Task lighting	Portable utility lights

Table 3.9 Gateway HF&H Reference Design

For these reasons, a shelf-stable food system was selected.

3.2.6.3 Reference Design Description

There are several degrees of functionality necessary to the HF&H design of the Gateway: eating, sleeping, ops, hygiene, exercise and stowage. These are listed and described by their physical manifestations in the spacecraft. They are further supported by equipment mentioned following the functionality section. Lastly, the medical capability of the vehicle is described. See Table 3.9 for the Gateway HF&H reference design.

Sleep accommodations provide each crewmember with at least the minimum volume of 1.5 m^3/person. Sleeping bags, similar to those used on Shuttle and ISS will be used to provide restraint for the crewmembers during sleep. Private areas of the minimum volume will be provided for each crewmember for sleeping and personal privacy as well as recreation. A crewmember can pull a provided retractable cloth out of its stowed position, which is rolled into the inner core of the vehicle. This cloth provides a wall, blocking out light and abating sound so that the crewmember may attain the minimum requirement of uninterrupted sleep. These temporary walls also serve as changing rooms, if the hygiene and waste collection facility is in use or not preferred for changing. When stowed, the cloth walls take up very little room, and the rolled-up sleeping bags collapse to 0.1 m^3/person.

Waste management is done within a plumbed facility similar to the ISS waste & hygiene facility. Solid and liquid waste is collected and processed with ECLSS hardware for water reclamation and solid waste storage. If technology advances, the Gateway waste management system could be used in conjunction with ECLSS hardware for solid waste recycling as well. The waste collection area is visually and audibly private, and confines hygiene and waste collection facility air using a carbon-based air filtering system and a retractable “ceiling”. The door to the commode faces a different direction from the eating facility, and the door opens in such a manner that further separates the two functions.

Exercise is available to the crew, though the mission’s nominal duration is relatively short. Based on the medical needs of the crew and the volume available in the Gateway, both cardiovascular and resistive exercise equipment will be provided. The specific equipment to be used for both of these exercise functions has yet to be selected, as technology development is still needed in this area. The exercise facility is in close enough proximity to both the hygiene area and access to potable water in the crew galley, though it may put the exercise area too close to the crew galley itself. This is remedied with a pull-curtain over the crew galley when a crewmember is exercising.

Hand washing is done with wipes located within the hygiene and waste collection facility wherever possible and stowed directly outside with the personal hygiene kits otherwise. The personal hygiene kit contains personal equipment for grooming. Full-body cleansing is also done in the hygiene and waste collection facility. The handwash/mouthwash faucet mentioned in Table 3.10 is similar to the water faucet developed for use on the ISS, and is located in the hygiene and waste collection facility.

Equipment/Supplies
Clothing
Disposable clothing (no laundry)
Personal Hygiene
Handwash/mouthwash faucet
Personal hygiene kits (4)
Hygiene supplies, including wipes for hand wash
Full-body cleansing hardware
Waste Collection System
Waste collection system supplies
Backup fecal/urine bags
Galley
Spigot for food hydration and drinking water
Cooking/eating supplies
Operational Supplies and Restraints
Operational supplies
Restraints
Maintenance
Tools
Test equipment
Housekeeping
Vacuum cleaner
Disposable wipes for housecleaning
Trash bags

Table 3.10 HF&H Equipment

The crew galley will be used to stow and prepare the food for crew consumption. Food stowage is readily accessible in the eating facility, in close proximity to both the food warmer and the rehydrator. Near the food warmer and rehydrator, a retractable board is provided for temporary food restraint during preparation. The wardroom table, when deployed, is adjacent to the crew galley, in the same volume as the stowed sleep accommodations equipment. Surfaces are easily cleaned, and packaging used for food and beverages is disposable, and therefore need not be sanitized.

Equipment for the waste collection system is provided in the form of consumables and contingency fecal/urine bags. These are stored within the waste collection facility wherever possible, and immediately outside the waste collection facility otherwise. In a contingency scenario, provided bags are easy to handle, simple to close, and have a designated storage area. This storage area is vacuum vented once full.

The following in Table 3.11 are the pieces of equipment supplied for Gateway medical support.

Stowage is provided in the form of soft stowage bags similar to the Cargo Transfer Bags (CTBs) being used on the ISS. The vehicle carries sufficient stowage to hold all of the mission's equipment, consumables,

Equipment/Supplies
Crew Health and Crew Safety (CheCS)
Health Maintenance System
Crew Contamination Protection Kit
Crew Medical Restraint System
Defibrillator
Medical Consumables
Ultrasound
Environmental Health System
Surface Sampler Kit
Water Microbiology Kit
Water Sampler and Archiver
Compound Specific Analyzer-Combustion Products
TLD Dosimeters
TLD Reader
Tissue Equivalent Proportional Counters
Microbial Air Sampler
Volatile Organic Analyzer
IVA Charged Particle Directional Spect.
EVA Charged Particle Directional Spect.
Spectrophotometer
Fungal Spore Sampler
Incubator
Countermeasures System
Blood Pressure/Electrocardiograph Monitor
Heart Rate Monitor
HRM resupply kit

Table 3.11 Gateway Crew Healthcare Equipment

and samples, as well as a small amount of personal stowage for the crew. Stowage is dispersed throughout the pressurized vehicle, being located such that functions are matched with related equipment and consumables. The racks originally designed for this equipment (on the ISS) are simplified to make stowage more accessible, and the rack less voluminous.

The lighting system for the Gateway station is two-fold. Solid-state lighting, in the form of LEDs, is placed throughout the cabin and is configured such that the light levels are appropriate for both ops requirements and human psychology. All lights are fully adjustable and fully dimmable by the crew from the off position to their maximum lighting capacity. Light levels may also be computer-controlled, for day simulation or variable light in cycles to provide a changing environment. Portable utility lights are available to the crew to use throughout the vehicle for more defined lighting in their work area, and can be applied to any function.

Clothing is lightweight and disposable. For privacy, either the crew can change in their curtained sleeping accommodations, or they can change in the hygiene and waste collection facility.

The spigot in the galley on the rehydrator accommodates food rehydration. Other cooking and eating supplies may include utensils, cleaning supplies, and small equipment needed for the rehydrator and food warmer. Shelf-stable food is packed in soft stowage until used.

Any supplies needed for operations on the Gateway are carried in the soft stowage, which include diskettes, ziplock bags, and tape, among other items to be determined. In addition, crew ops restraints and mobility aids (R&MA) are installed throughout the Gateway. Those restraints are installed such that there exists a local vertical where crewmembers are working. Restraint and mobility aids are also removable and reconfigurable throughout the vehicle to provide flexibility for the crew.

Maintenance equipment includes both tools and test equipment. Tools such as hand tools and accessories are located in the soft stowage containers that are closest to where the tools would be used. Test equipment may be installed in the cabin, but is otherwise stored in soft stowage until needed. Test equipment includes oscilloscopes, gauges, and other instruments to be determined. Varieties of housekeeping supplies are needed to further maintain the Gateway. A vacuum is provided for the crewmembers to use and stowed with two spares. Disposable wipes are also useful in cleaning surfaces, and all the expended packaging and consumables are to be placed in trash bags that are provided and stowed appropriately.

Gateway HF&H		
Component	**Mass**	**Volume**
Galley	501	4.046
Crew Quarters	592	1.700
Hygiene Facility	116	2.179
Exercise Facility	305	0.737
Waste Collection Facility	101	0.737
Wardroom	25	0.135
Workstations	88	1.366
Science Equipment	120	0.500
Maintenance Tools	236	1.180
Acoustics	0	0.000
Lighting	76	0.090
Space Medical Facility	348	2.341
Total	**2,507 kg**	**15.0 m^3**

Table 3.12 HF&H Summary

A summary of the physical attributes of the Gateway human factors and habitability design may be found in Table 3.12.

Finally, the human factors and habitability design efforts focused on determining the

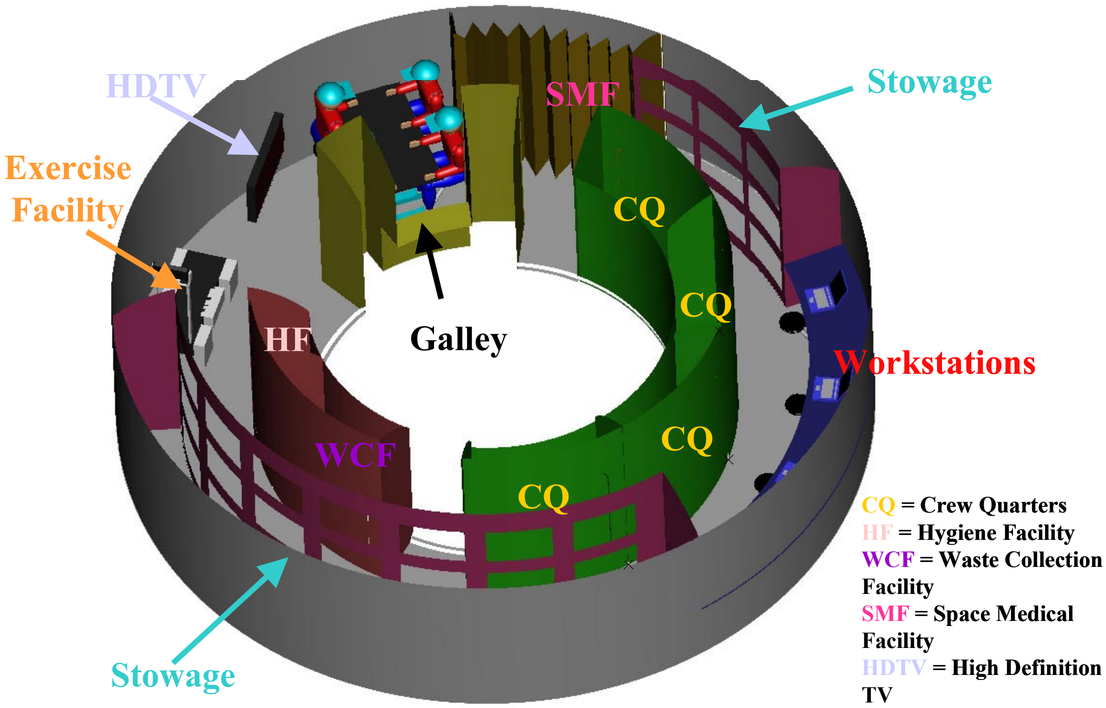


Figure 3.12 Inflatable Section Layout

layout of the inflatable volume. This area is where the crew will spend the majority of the time during the mission, and should be arranged for optimal crew use. The major areas in the layout include four individual crew quarters, an exercise facility, crew galley, a hygiene and waste collection facility, a medical facility, workstations, and large volumes for equipment stowage. These areas were grouped and packaged according to functionality and crew interaction. Passage between the Gateway core and the habitable space is permitted through three individual pass-through sections. Layout of the aforementioned equipment within the inflatable section of the Gateway is illustrated in Figure 3.12.

3.2.6.4 Technology Needs and Design Challenges

Windows: Requirements for sizing the window still need to be investigated, and dimensions need to be developed, based on the required field of view for docking, and any other related ops. Simulated windows may also provide light and psychological comfort to the crewmembers, thus should be examined with this purpose in mind.

Sleep Accommodations: A small modification needs to be made to the sleep restraints so that they interface efficiently with the inner wall of the vehicle. Pull curtains need to be developed to create private spaces and separate sleeping areas for the crewmembers – this design need not be complex.

Hygiene: Full-body cleansing technology needs to be developed. Primary considerations for development should be minimal power, minimal crew time (including set up and clean up), and minimal excess water waste.

Medical Research: More research can be done into micro-gravity medical equipment and procedures, to further extend the medical capacity of the vehicle.

Exercise: Exercise technologies need to be investigated to determine what equipment will provide the best resistive and cardiovascular training in the small volume provided.

Food Supplies and Preparation: Refrigerator and freezer techniques can be further investigated and developed, such that shelf-stable food is not the only option for crewmembers. Oven technologies can also be researched, with a focus on not overtaxing the heat exchanger on the vehicle. Advanced food development may also lead to more meal options. The rehydrator and food warmer will need to be modified and sized down to fit in the Gateway such that crewmembers can work around them without too much difficulty.

Controls and Crew Interfaces: Advanced controls and displays can be investigated and/or developed.

Lighting: The solid-state lights (LEDs) must be installed in the vehicle, and this may require some modification of their design. Fiber optics may be considered to "pipe in" lighting.

Stowage: The current soft rack system being used with the soft stowage on the ISS must be simplified before installation in the Gateway.

The overall TRL of the human factors and habitability design is considered at eight.

3.2.7 Propulsion System

Propulsion systems are needed to provide both major and minor energy changes to a spacecraft. These changes, usually in the form of velocity addition and subtraction, are used to alter orbits and spacecraft attitudes. For the L_1 Gateway, propulsion needs are in the form of position maintenance, or "station-keeping". As the Gateway is located at the weakly unstable collinear Lagrange point L_1, disturbances will cause the spacecraft to drift away from the point, therefore it must expend propellant to remain stationary. For major energy changes such as delivery from LEO to LL_1, the Gateway is transported by the Solar Electric Propulsion (SEP) Stage, therefore does not have to expend its own propellant.

3.2.7.1 Functional Description

The function of the propulsion system is to provide the Gateway with approximately 50 m/s ΔV per year for the lifetime of the spacecraft. Previous studies have examined the cost of station-keeping at the collinear equilibrium points, with results as low as less than one m/s ΔV per year.[7] However, these studies generally assume infinitesimal thrust capability with perfect navigation state knowledge, assumptions which are not practical for real-world application. For the Gateway, it was assumed that the annual velocity change would be equivalent to that required for keeping a geostationary satellite on station. Further study should be performed to determine the true station-keeping requirement.

The Gateway vehicle has a lifetime of 15 years with resupply missions every two years. This resupply schedule splits the total lifetime ΔV of 750 m/s to 100 m/s per resupply, which significantly reduces tank size and propellant mass. Attitude control for the Gateway is not done propulsively, rather is performed by the momentum-exchange flywheel system. Momentum dumping for the ACS is performed by power shuttering between the flywheels, though any additional needs could potentially be handled by the Gateway propulsion system. To avoid contamination concerns during telescope assembly missions, station-keeping maneuvers will only be performed when the Gateway is uninhabited, which is approximately nine months out of the year.

3.2.7.2 Trades Considered

Several potential propellant combinations were analyzed for the Gateway. These included:

- Tridyne ($N_2/H_2/O_2$)
- Monopropellant hydrazine
- Nitrogen tetroxide / monomethylhydrazine (NTO/MMH)
- Liquid oxygen / liquid methane (LOx/LCH_4)

Propellant combinations were evaluated based on performance, mass, volume, reactant products, and storability. Trade results are summarized in Figure 3.13.

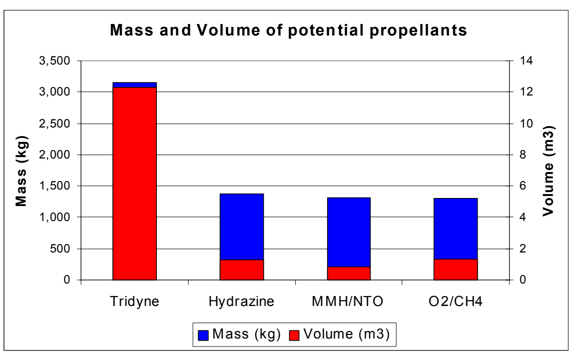


Figure 3.13 Propellant Trade Results

The studies showed that tridyne is a low performance, high mass and volume system, though the reactant products are non-corrosive. However, the sizeable difference in mass and volume made this a non-practical option. Monopropellant hydrazine has better mass and volume characteristics than does tridyne, though hydrazine is extremely toxic and has low performance as compared with a bipropellant system. The next system studied was MMH/NTO, which has higher performance than either tridyne or hydrazine, however MMH/NTO is extremely corrosive and toxic, which raises the issue of contamination of nearby elements.

The final option studied was a cryogenic LOx/LCH_4 propulsion system, which will be implemented for this design. This bipropellant system was selected due to its lower volume and propellant mass. Active cooling of the cryogens results in lower mass tanks and higher overall system performance. The LOx/LCH_4 exhaust product is non-corrosive, which eliminates the risk of contaminating near-by solar arrays. Choosing liquid oxygen as an oxidizer also allows common tanks to support other on-board systems. Finally, this choice of propellant combination enables commonality with other elements in the Gateway Architecture, as they have also implemented similar systems. Within the choice of LOx/LCH_4, further trades were run on the number and shape of the cryogenic propellant tanks.

3.2.7.3 Reference Design Description

The propulsion system chosen for the Gateway will be a liquid oxygen/liquid methane bipropellant combination at a mixture ratio of 3.8:1. There are twelve pressure-fed, 110 N engines capable of 322 s I_{sp}, one spherical oxidizer tank (1.33 m OD), and one spherical fuel tank (0.96 m OD). The twelve thrusters are arranged in three pods of four thrusters each in order to provide thrust in all three spacecraft axes. An analysis of L_1 orbit degradation and station-keeping maneuvers may reveal detailed thrust pointing requirements, but these were unavailable at the time of this study. Active cooling for the Gateway tanks requires 64 W of input power, with an efficiency of 15 W of input power per Watt of cooling. In addition to storing oxidizer for Gateway station-keeping, the liquid oxygen tank will provide

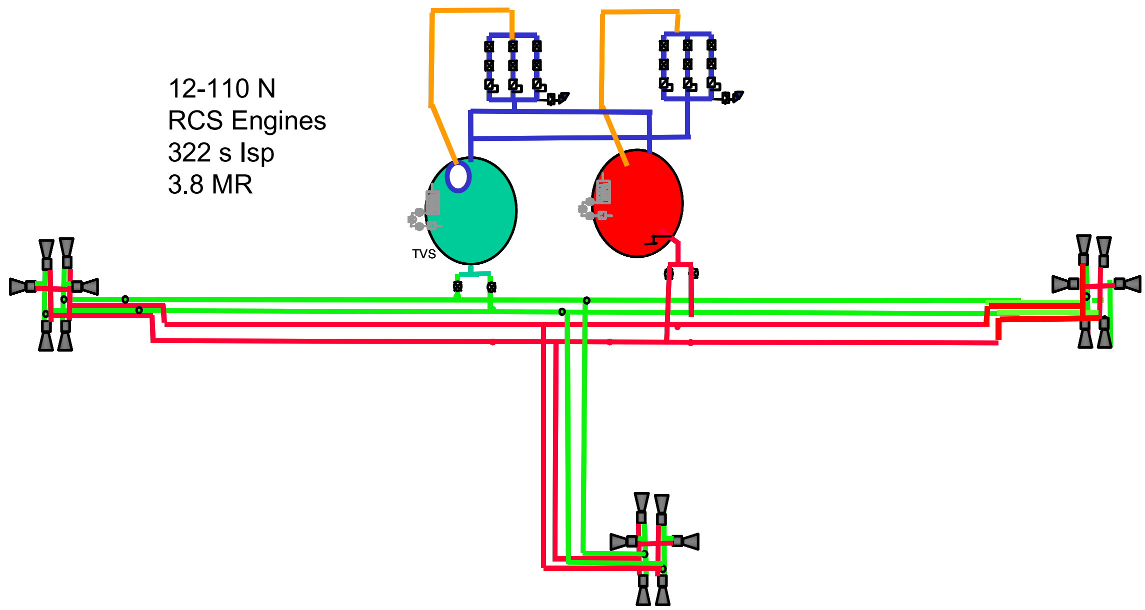


Figure 3.14 Gateway Propulsion System Schematic

491 kg of cryogenic oxygen to the ECLSS and EVA system. By combining these functions in the propulsion system, the mass of an additional tank and associated hardware can be saved.

During resupply, the empty propellant tanks will be removed by the Gateway RMS and replaced with full tanks. A single cargo pallet housing both tanks is envisioned for ease of operation. As previously mentioned, resupply of the Gateway will occur on a two-year cycle. The resupply frequency was primarily driven by total propellant mass and initial launch capability, though the cost impact of this decision should be further analyzed. A more frequent resupply schedule will reduce total mass per mission at a cost of additional launches. A schematic of the Gateway propulsion system is shown in Figure 3.14, and Table 3.13 summarizes the Gateway propulsion system.

Propulsion System	
Requirements	
Delta-V (m/s/year)	50
ECLSS/EVA O_2 (kg)	491
Resupply Frequency	2 years
System Summary	
Mass (kg)	1,444
Tankage (kg)	176
LOx (kg)	1,106
LCH_4 (kg)	162
Volume (m^3, O_2/CH_4)	1.23/0.46

Table 3.13 Propulsion Summary

3.2.7.4 Technology Needs and Design Challenges

Technology needs for this design are flight-qualifying the 110-N LOx/LCH_4 engines and lightweight pulse tube cryocoolers. These components are currently estimated at a TRL of four.

A significant design challenge for this system is thruster placement on the spacecraft. Plume impingement is always an issue, but for the Gateway, there are few placement options. Thruster pods must be located where they will be most effective and not impinge on near-by structures. The issue with thruster placement relates to the inflatable outer structure of the Gateway. One concept offered as a solution is using large support booms that will hold the thruster pods at the required locations. These booms will transmit loads to the core pressure shell at minimal moment impacts without needing to physically fasten the thruster pods to an inflatable skin.

3.2.8 Robotics System

The robotics system on the L_1 Gateway is designed to provide a variety of capabilities including support of EVA activities and maintenance, and inspection and mobility of both intra- and extra- vehicular systems. To allow maximum flexibility in supported payload size, level of autonomy and operational dexterity, two distinct robotic systems are employed. The first is a Space Shuttle-class robotic arm (Remote Manipulator System (RMS)), and the second is a state-of-the-art humanoid robot, Robonaut, currently under development at NASA's Johnson Space Center.

3.2.8.1 Functional Description

Remote Manipulator System: The functional top-level requirements that led to the selection of this system for the Gateway are as follows:

- Provide capability for gross manipulation of external payloads
- Provide support for EVA crew manipulation
- Provide support for telescope construction and other scientific missions

The RMS is proven technology that has been utilized on-orbit since STS-2 in 1981. Figure 3.15 shows the RMS supporting a

Figure 3.15 Shuttle RMS

Space Shuttle EVA operation during STS-82. Although the scale and size of robotic arm components can be adjusted to satisfy specific L_1 Gateway design criteria, it has a payload capability that concurs with expected Gateway mission scenarios. The Gateway robotic arm will consist of an upper and lower arm boom, with a 3-degree-of-freedom (DOF) pitch and yaw shoulder joint, 1-DOF elbow pitch joint, and a 3-DOF pitch, roll and yaw wrist joint. Specifications for the arm are detailed in section 3.2.8.3. The RMS will be launched in the Shuttle payload bay, and will be attached to the Gateway as part of the Shuttle outfitting mission.

Robonaut: One approach to utilizing EVA resources more effectively while increasing crew safety and efficiency is to telerobotically perform routine and high-risk EVA tasks. In response, NASA's Johnson Space Center (JSC) is developing an anthropomorphic telerobot called Robonaut that is capable of performing tasks normally required of an EVA crewmember. Figure 3.16 shows Robonaut in development. As Robonaut is similar in size to a suited crewmember, it can utilize the same airlock that astronauts use to traverse between the interior and exterior of the Gateway.

Figure 3.16 Robonaut

Not depicted in Figure 3.16 are the Robonaut tail section and worksite interface (WIF) socket. Robonaut may either be positioned on the end of the RMS or plugged into an external WIF socket. Figure 3.17 shows a representation of Robonaut working on the exterior of the Space Station. Notice at the bottom of the figure the Robonaut tail section and WIF socket.

The top-level functional requirements that led to the selection of Robonaut for the Gateway are as follows:

- Provide dexterous aiding / augmentation to EVA operations
- Provide dexterous intra-vehicular activity system maintenance / contingency operations
- Provide dexterous support for telescope construction and other scientific missions

Robonaut requires the operator to command over forty-seven degrees of freedom while performing full immersion telerobotic tasks. Unlike the arm operator that is situated in front of a control station with joysticks, an IVA Robonaut teleoperator wears a variety of virtual reality display and control technology to immerse himself or herself in the robot's workspace, thereby creating a sense of 'presence' at the robot worksite. The user's body position, tracked by an array of sensors, is sent as a command to the robot software that in turn generates robot motions. Robonaut features two cameras for eyes and the live video feed received from them is sent to a helmet-mounted display (HMD) such that the human sees through the HMD what the robot sees. A transmitter is also mounted on the helmet so the mo-

Figure 3.17 Robonaut Working on ISS Exterior

Figure 3.18 Robonaut Workstation

tions of the user's head are tracked. As the operator moves his/her head to the right or left, the robot likewise turns its head. In this way, the human feels that they are immersed and present at the robot site working the tasks themselves. Figure 3.18 shows an operator seated wearing the telepresence hardware.

Robonaut may be controlled from a ground station with signal delays. This will allow Robonaut to carry out a number of IVA maintenance and contingency operations while the Gateway is unoccupied. The Robonaut telepresence workstation is under construction, thus the components used for the Gateway robotic system may vary from those presented. However, akin to the RWS, the Robonaut workstation components will be stored within an ISPR and deployed on-orbit. Robonaut itself is also under construction and therefore the levels of autonomous operations it is capable of performing will be continually increasing, further expanding its functionalities as time progresses.

Robotic Workstation: The RMS is operated remotely (teleoperated) from an intra-vehicular workstation. The robotic workstation (RWS) consists of three flat-panel display monitors, a control electronics unit, one display control panel, a portable computer system (laptop), and two hand controllers (translation and rotation). If necessary, this control can also be achieved from remote stations at a cost of time-delayed signals to the hardware. Workstation components similar to these are employed for the L_1 Gateway robotic arm. These components will be stored in a unit similar to an International Space Station Payload Rack (ISPR) upon launch, then deployed and configured by a crewmember during the planned Shuttle outfitting mission. Volume estimates for the RWS are based upon the volume of an ISPR. However, additional components on the RMS workstation are launched within the ISPR for the ISS program that are not necessary for Gateway operations, therefore the ISPR volume should be considered an upper limit for this system. The robotic workstation is represented in Figure 3.19.

Figure 3.19 Robotics Workstation

3.2.8.2 Trades Considered

Few trades were considered for the Gateway robotic system. However, a decision had to be made as to the number of robotic arms to have on-board. It was certain that an arm needed to be available for EVA operations at one end of the Gateway. At the outset though, it was not clear whether the robotic system needed to support relocation of vehicles docked at or visiting the Gateway on the opposite end. If so, this would require either one arm large enough to "inchworm" across the Gateway structure, or two smaller arms, with one at either end. Once the requirement for vehicle manipulation was eliminated, it was determined that a single arm located at the EVA staging area of the L_1 Gateway would be sufficient.

In regard to the size of the arm, the driving requirement was the potential for Gossamer telescope operations assistance. Initially the constraint was to support the construction of a large 40-m aperture telescope structure. After revisions were made by telescope designers that reduced the size of the mirror aperture to 25 m, it was determined that an arm comparable in size to the current Shuttle RMS would meet telescope and other large payload requirements.

The desire to perform dexterous functions both inside and outside the Gateway limited the choice of manipulators to the Robonaut, although other types of non-humanoid dexterous robots are in existence. In the event of an issue or contingency arising on the Gateway while uninhabited, Robonaut provides the technology to perform the repair or maintenance as if the crewmember were present. Robonaut requires no special tools or interfaces to any on-board systems, and may be unstowed, translated to the worksite, and operated from ground.

3.2.8.3 Reference Design Description

Robotic Manipulator System: The values listed below in Table 3.14 are for a robotic arm with the exact specifications as the Shuttle RMS. The manufacturer has rated the maximum payload capacity to be 266,000 kg.

Gateway Robotics			
Component	**Mass**	**Volume**	**TRL**
Robotic Arm	452	1.746	9
Robotics Workstation	91	4.295	8
Robonaut	136	0.713	5
Robonaut Workstation	10	0.250	5
Total	**689 kg**	**7.0 m^3**	

Table 3.14 Robotics System Specifications

Robotics Workstation: The mass and volume of the RWS in its deployed configuration are listed in Table 3.14.

Robonaut: A total volume for the Robonaut components can be calculated, however the stowed volume of Robonaut is difficult to discern as it can be placed in a variety of configurations. As Robonaut is sized to compare to a suited astronaut, it is expected that its stowed volume will not exceed that of the Extravehicular Mobility Unit (EMU).

Robonaut Workstation: The Robonaut Workstation is still under development, thus values reported in Table 3.14 reflect specifications of the current hardware. This hardware includes the HMD, tracking gloves, tracking sensors and two laptops. The dimensions and volume of the complete system are also undetermined, yet will not exceed that of an ISPR.

3.2.8.4 Technology Needs and Design Challenges

All technology needs for the Gateway robotics system fall under the Robonaut system. As robot and workstation construction continues, new components are incorporated as they become available. A complete system is expected within three years. Currently, technology needs revolve around the workstation; a posture tracking system and suite of situation awareness displays and operator aids are still under development. The posture tracking system currently used for Robonaut is insufficient for on-orbit function, though new technologies are being evaluated in-house as workstation design continues. Likewise, situation awareness aids including visual, auditory and force feedback mechanisms are being designed and implemented. Robonaut and its workstation have a TRL of five. The RMS and robotic workstation are currently in operation, thus qualify as TRL 9.

3.2.9 Structure

As discussed in the system overview, the Gateway structure design is a hybrid system with a core pressure shell for stowing equipment during launch and attaching external systems, and an inflatable torus section for providing a large primary habitable volume. The Gateway has three docking ports for visiting vehicles and for logistical re-supply flights. It also provides an external work site for the construction and servicing of telescopes, and consists of an EVA platform, a robotic arm, and a cupola window.

3.2.9.1 Functional Description

The Gateway will be launched to Low Earth Orbit on a Delta IV Heavy. Acceleration loads for launch are 6 g's in the axial direction and 2.5 g's in the radial direction, which envelope any loads experienced during the spiral to Lunar L_1. It supports an internal pressure of 62.0 kPa and must provide 275 m^3 of pressurized volume to the crew. The Gateway will remain on-station at LL_1 for fifteen years. The Gateway structure must also provide micrometeoroid and orbital debris (MM/OD) impact penetration and crew radiation protection.

3.2.9.2 Trades Considered

As the configuration of the Gateway had been predetermined, the only major trade for the structural design involved the visiting vehicle docking system. For the three docking ports required, it was determined that the best approach would be to utilize the inflatable airlock design chosen by EVA and outfit the structure with appropriate docking mechanisms. To support three vehicles in one confined area while maintaining approach envelope restrictions, the docking ports must be separated by as much distance as possible. In order to overcome launch vehicle payload diameter limits, which inhibit the ability to provide large separation distances, an inflatable system was a natural solution. An inflatable docking port could also be deployed or retracted as needed, and would extend beyond the reach of a rigid structure. In addition to enabling commonality with the EVA system, the inflatable docking port allowed for mass savings over the competing options.

3.2.9.3 Reference Design Description

The Gateway pressurized volume consists of a cylindrical core pressure shell 6.5 m long and 4 m in diameter, and an inflatable torus 9.4 m in diameter.

The inflatable skin design for the Gateway is derived from the TransHab module developed at NASA Johnson Space Center. It is a composite skin with individual layers dedicated to support certain functions. The innermost layers consist of a liner, a bleeder and bladder, and a restraint layer. These function as a pressure vessel to maintain the internal atmosphere. To serve as protection against MM/OD impacts, an outer bumper shield is integrated with the inner layers. The shielding concept consists of seven Kevlar sheets and four layers of Nextel fabric, with each Nextel layer separated by an open-cell lightweight foam spacer. The overall thickness of the bumper shield is 11 cm. For the inflatable skin, a risk-based design approach was taken to determine the number of layers required. Across the 15-year lifetime of the Gateway, a 95% probability of no penetration (PNP) was accepted, and this bumper shield design will meet that requirement.

The mass of the inflatable skin inner layers was scaled based on the ratio of the Gateway inflatable skin surface area to the TransHab surface area. There were no additional changes made for design of the Gateway skin inner layers, as results from the TransHab study were found to be sufficient and did not warrant further analysis. The Gateway inflatable section is a torus shape, with a major diameter of 9.4 m, a minor diameter of 3 m, and total surface area of 176 m^2.

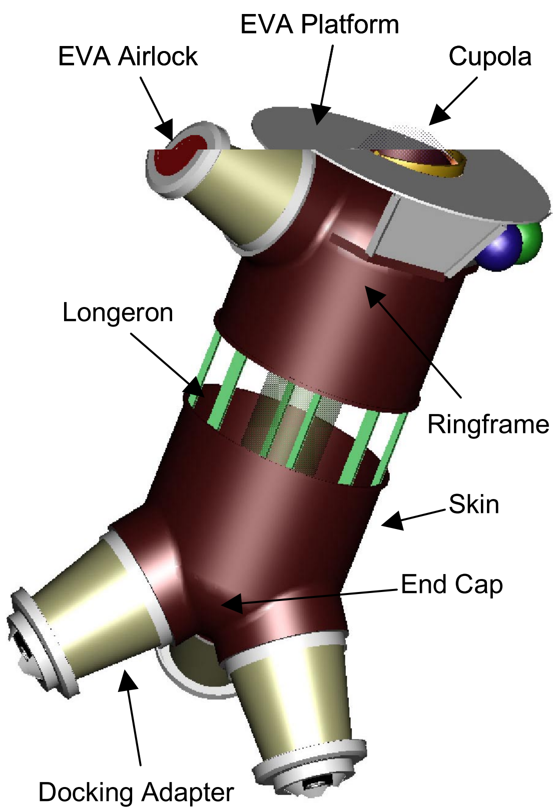


Figure 3.20 Core Pressure Shell

The Gateway core pressure shell (Figure 3.20) is a circular cylindrical tube with ellipsoidal end caps. There is a passageway cut in the middle of the core that allows for entrance to the inflatable volume from the core. The major components of the core are two end caps, eight longerons that run the length of the core, the skin, and ring frames. The eight box-beam longerons are equally spaced around the circumference of the core. Of the ring frames, two are placed at the seam between the end caps and the cylinder, and two are used to constrain the inflatable skin to the core. All components of the core are constructed with an aluminum-lithium alloy, Al-Li 8090-T852, which was selected for its high strength to weight ratio, stiffness to weight ratio, and manufacturability. Regions of the core exposed to the space environment will be protected against MM/OD impact with a bumper shield identical to that found on the inflatable skin. Four layers of Nextel cloth and four layers of open-cell foam protect the 97 m^2 of core surface area to a 95% PNP.

Analysis was performed to size the different elements of the core. The loading conditions were the internal pressure of 62.0 kPa (9.0 psia) and the acceleration loads from the Delta IV Heavy launch. A factor of safety of two was used in all analyses for sizing members. In addition to withstanding internal pressure, the top end cap was sized to bear the load of three docking ports during launch. Therefore, the thickness of the end cap skin was increased to account for this load. It was assumed that the launch loads enveloped any loads the top end cap would bear during docking/berthing operations of other vehicles.

As most of the launch acceleration loads run along the axis of the core, eight longerons were placed in the core to withstand the axial load. The longerons span the length of the core from the top seam between the end cap and the cylinder to the lower seam between the end cap and the cylinder (approximately 6.5 m). They are placed equidistant around the circumference of the 4 m diameter core, and are sized for buckling and bending load cases. The estimated weights of other systems as well of the weight of the core and uninflated skin were used in determining the total load expected during launch. Each longeron was modeled as a square tube made from Al-Li 8090-T852. In both the buckling and bending analysis, the longeron was assumed simply supported at the ends. An appropriate square tube cross-section was selected.

An opening near the center of the core provides a passageway to the inflatable volume. The inflatable skin is constrained to the core above and below the core opening with ring frames. The ring frames were conservatively designed to have the same cross-section as that determined for the longerons.

In addition, due to the stress and displacement discontinuity between the end caps and cylinder portions of the core, ring frames were placed at the seams. Similar to the two other ring frames, these were conservatively designed to have the same cross-section as that determined for the longerons.

An interstage adapter provides an interface between the Gateway and the Delta IV Heavy launch vehicle. It is modeled as a hollow skin-stringer cylinder made from Al-Li 8090-T852, and is connected to the Gateway at the EVA platform. The interstage adapter is under considerable axial load with a buckling primary mode of failure during launch. The adaptor is long enough to extend past the cupola.

As mentioned, there are three docking adapters on the Gateway. Each adapter consists of three major components: an International Berthing and Docking Mechanism (IBDM), the inflatable airlock, and airlock support struts. Once on-orbit, the inflatable

Gateway Structure				
Component	**Qty**	**Mass**	**Material**	**TRL**
Inflatable Skin	-	1618	Multi-layer (TransHab)	4
Core Structure	-	1356	-	8
Longerons	8	-	Al-Li 8090	9
Skin	-	-	Al-Li 8090	9
Hardpoint	-	-	Al-Li 8090	9
MM/OD Protection	-	176	Multi-layer (TransHab)	4
Interstage Adapter	1	200	Al-Li 8090	9
Docking Adapters	3	1997	-	3
Inflatable Airlock	3	1091	-	3
Support Struts	15	90	Al-Li 8090	9
IBDM	3	816	-	4
EVA Work Platform	1	100	Al-Li 8090	9
Platform Support Struts	8	264	Al-Li 8090	9
ORU/Robot Storage	1	150	-	9
Radiation Protection	-	0	-	-
Cupola	1	198	Lexan	7
Secondary Structure	-	1471	-	9
Total		**7,354 kg**		

Table 3.15 Gateway Structure Design Summary

airlocks are deployed and the support struts help maintain the airlock's shape and provide resistance to any docking loads. The IBDM is a robust docking mechanism and is selected for commonality with other elements in the Gateway Architecture.

The EVA platform is essentially a 6 m diameter disk with a cutout to allow for the cupola. It is connected to the Gateway with eight struts at the seam ring frame of the cylinder and the end cap. The method employed to size the eight struts that connect the EVA platform to the Gateway core structure was similar to the manner in which the core longerons were designed. These eight struts must support the total weight of the Gateway under the launch loads. Each strut was modeled as a square tube made from Al-Li 8090-T852. In the buckling analysis, the strut was assumed simply supported at the ends. For bending analysis, it was conservatively assumed that the struts were cantilevered at one end and that the load was concentrated at the other end. An appropriate square tube cross-section was selected.

The secondary structures in the Gateway, which include fasteners and support structures for subsystem boxes, was assumed to be 25% of the Gateway primary structure mass.

Table 3.15 above summarizes the Gateway structure design.

3.2.9.4 Technology Needs and Design Challenges

A major technology need for the Gateway structure is long-duration material exposure data at Lunar L_1. Beyond LEO, a spacecraft is subjected to high levels of ultraviolet radiation, galactic cosmic rays, and solar particles. This radiation can break long polymer chains, such as those in the inflatable section, and may cause premature degradation of the Gateway structure. A long-duration exposure facility experiment may be a necessary precursor to manned missions at the Gateway. Another concern of the inflatable section involved the bladder layer material. This material, RTV urethane, suffers from permeability issues and is highly sensitive to wide temperature fluctuations. Additional analysis is required to determine the applicability of this material for the Gateway.

There was research performed into self-healing composite materials for use as secondary structures. Typically, the material is a plastic with several embedded microcapsules. When cracks in the plastic run into one of the microcapsules, the capsule breaks and leaks a liquid healing agent into the crack. The liquid healing agent fills in the crack and then dries. Essentially, the liquid healing agent is glue that repairs the crack. Self-healing structures may hold promise for future iterations of the Gateway study, however they were not incorporated at this time.

3.2.10 Thermal Control System

The Gateway thermal control system (TCS) is responsible for maintaining appropriate internal operating temperatures within limits dictated by system hardware and crew comfort requirements. To accomplish this, the TCS is designed to provide and reject energy in the form of heat to and from the habitable volume. In order to accommodate the various environments in which the Gateway will operate, the TCS features a robust architecture that utilizes both active and passive thermal systems.

3.2.10.1 Functional Description

The Gateway TCS provides cooling for a nominal thermal load of 13.5 kW based on the anticipated maximum nominal vehicle power consumption for any mission phase. Additionally, the TCS provides 2.1 kW of cooling for parasitic thermal loads from the power system. The power system generates this parasitic thermal load due to inefficiencies and cooling for energy storage batteries inside the crew cabin. Thus, the overall nominal TCS cooling capacity is 15.6 kW. Once on-orbit and under the nominal mission flight plan, the Gateway operates in free space for its entire operational life. During all mission phases from Low Earth Orbit (LEO) to the final destination at the Lunar Lagrange point (LL_1), the Gateway can reject thermal loads to its environment using radiators.

The Gateway TCS acquires thermal loads via cabin heat exchangers, which extract heat from the cabin atmosphere, and cold-plates, which gather heat loads directly from hot components. A single phase, 60% propylene glycol ($C_3H_8O_2$) / 40% water fluid loop then transports the heat loads to the radiators for rejection from the vehicle. In addition to rejecting internally generated thermal loads, there are several other needs in this design associated with temperature control. The Gateway must sustain visiting vehicles above minimum operating temperatures, maintain docking mechanisms within an acceptable temperature range, and manage internal and external touch temperatures for crew safety.

A significant TCS design challenge with lower temperature limits in the habitable volume is found at the pressure vessel wall. If the cabin wall temperature drops below the dew point of the internal atmosphere, water condenses on the cabin wall. For the International Space Station, the minimum allowable wall temperature is 288.7 K (60 °F). As this is greater than the minimum temperature requirement for any other system, an acceptable wall temperature provides the lower temperature bound for the cabin.

For the Gateway, the minimum assumed cabin wall temperature is 285.9 K (55 °F). However, as the pressure vessel wall temperature associated with natural vehicle energy balance is less than 285.9 K, resistive heating elements will provide heat as needed to maintain minimum wall temperature. For system components packaged outside the pressurized volume, these are assumed to withstand the minimum temperatures associated with the operating environment, though detailed study may reveal additional demand for localized resistive heating elements.

With the inflatable portion of the L_1 Gateway, it is assumed that airflow design will provide enough heat convection to sustain the fabric inner wall above the minimum assumed temperature of 285.9 K (55 °F). As experience with inflatable technology progresses, it may become feasible to place heaters on the inner wall, however this study assumed that heaters on the inflatable fabric were not an option at this point.

Passive system approaches are used to address other temperature concerns. Internal touch temperatures are maintained within the acceptable range for crew comfort through proper material selection and thermal design. More specifically, each individual component must safely dump its thermal load to its designated thermal sink while maintaining crew-compatible surface temperatures. External touch temperatures, an issue associated with EVA only, are maintained within acceptable bounds by use of EVA-compatible hull surface properties and appropriate vehicle attitudes. Resistive heating elements may be necessary following in-depth analysis, but active cooling appears unnecessary.

3.2.10.2 Trades Considered

The primary trades considered in this study were the fluid loop architecture, radiator configuration, total number of radiator panels, and TCS fluid composition. As the design team was limited to using inflatable technology for the habitable volume structure, this constraint offered extensive surface area for placement of some type of body-mounted radiator. Another advantage to making use of the inflatable section on the Gateway was that placement of the radiators on this surface would insure that they would face deep space and not the Sun for most of the mission, thereby enhancing heat rejection capabilities. Thus, it was assumed that the radiator panels would always face deep space, and were sized accordingly.

For the heat rejection system, three individual radiator panels were baselined to improve redundancy in case of a loss of any one panel. Due to a lack of redundancy, a single panel would be insufficient, and two would cause a 50% reduction in the heat rejection capability if the other were rendered unusable. With three panels, a loss of one lowers the heat rejection capability by only 33%. Without further detailed analysis regarding mission specific heat rejection requirements, it was assumed that this would be an acceptable risk. Therefore, the final design featured three radiator panels.

The second TCS trade study considered the architecture of the fluid loops. For thermal control, it is expedient to transport heat over relatively long distances, such as those associated with L_1 Gateway, using a working fluid in a closed loop as a transport medium. In one option, a continuous fluid loop serves both the heat acquisition devices, including those in the pressurized volume, and flows through radiators directly. In another option, one fluid loop serves the heat acquisition devices and transfers heat load to a second loop that passes through radiators.

Issues of importance here include crew safety, overall mass, reliability, and availability. Crew safety is a concern if the working fluid serving the heat acquisition devices in the cabin is toxic, as the crew may encounter the working fluid if a leak occurs. Availability to reject heat is another concern. The L_1 Gateway TCS design assumes freeze-tolerant radiator panels. However, if the solidification temperature of the working fluid passing through the radiators is too high, those radiators may not provide sufficient unblocked flow passages, and thus sufficient area, to reject the complete heat load.

Using a single continuous flow loop is less massive and more efficient than using two flow loops to reject the same load. However, any continuous flow loop must employ a working fluid that is not toxic to the crew and sufficiently freeze-resistant to its operating environment such that radiators are available when necessary. Multiple flow loops may use a non-toxic working fluid, such as water, to serve the habitable volume and a second freeze-resistant fluid, such as ammonia, to serve the radiators. However, multiple flow loops use twice as many pumps and require an interface heat exchanger, therefore are more massive and complex. Assuming non-toxic, freeze-resistant working fluid, a single continuous flow loop is the preferred approach here. Complete resolution of this issue requires in-depth thermal environment of the L_1 Gateway.

Another TCS trade considered the category of body-mounted radiator to use. Flexible flow-through radiators were baselined over flexible heat pipe radiators based primarily on mass. Data from radiators currently being tested in the Crew and Thermal Systems

Figure 3.21 Flexible Thermal Radiators

Division at JSC indicate that the flexible heat pipe radiators mass per unit area is almost double that of flexible flow-through radiators.

One advantage of the flexible heat pipe radiators is they offer better redundancy than flow-through radiators, as a heat pipe radiator panel is made up of multiple independent heat pipe sections. If a panel composed of six heat pipes loses one section to orbital debris impact, the panel only loses 1/6 of its heat rejection capability. However, if a flow through radiator panel were to take a similar hit, it would lose at minimum 1/2 of its rejection capability. Due to the reduced threat of MM/OD impact at Lunar L_1, though, it was decided that the lower mass of flexible flow-through radiators offset its redundancy shortcomings. In addition, a heat pipe radiator would most likely utilize a more toxic working fluid such as ammonia, and this was viewed as a disadvantage. Figure 3.21 illustrates the aforementioned flow-through radiators.

The final TCS trade considered which working fluid to use for the flow loop. The fluid selected was a mixture of 60% propylene glycol and 40% water. This selection was based upon a desire for commonality with other vehicles docked to Gateway (CTV will utilize the same fluid mixture) and perceived freeze tolerance of the mixture. For freeze tolerance, the relevant options are pure water, a mixture of propylene glycol and water, or some other working fluid. While water is non-toxic and has the highest thermal capacity per unit mass of any working fluid, it also freezes at 273.2 K and thus may not allow sufficient radiator availability for some mission phases.

A fluid combination of propylene glycol and water is also non-toxic, though it is a less desirable thermal working fluid than pure water. Safety literature reveals that pure propylene glycol is a mild irritant to human facial tissue and slightly flammable. When combined with water, the mixture is not flammable, but it may remain a facial irritant. However, it freezes at roughly 223 K, a significant advantage over water.[8] Thus, the tentative working fluid for the thermal control fluid loop is 60% propylene glycol with 40% water. As above, complete resolution of this issue also requires in-depth thermal environment modeling focusing on radiant heat rejection from the Gateway.

3.2.10.3 Reference Design Description

As mentioned in the trades section, the Gateway TCS employs a single-phase, pumped fluid loop to transport waste thermal energy between sites of heat generation and equipment for heat rejection. Heat is acquired by the TCS working fluid using cabin heat exchangers and coldplates. The heat exchangers remove both sensible and latent heat from the cabin atmosphere, and coldplates remove heat directly from equipment and electronic components. Here the heat itself is a TCS responsibility while condensate and atmospheric humidity loads are controlled by the environmental control and life support system (ECLSS). A radiator bypass has been added to allow for control

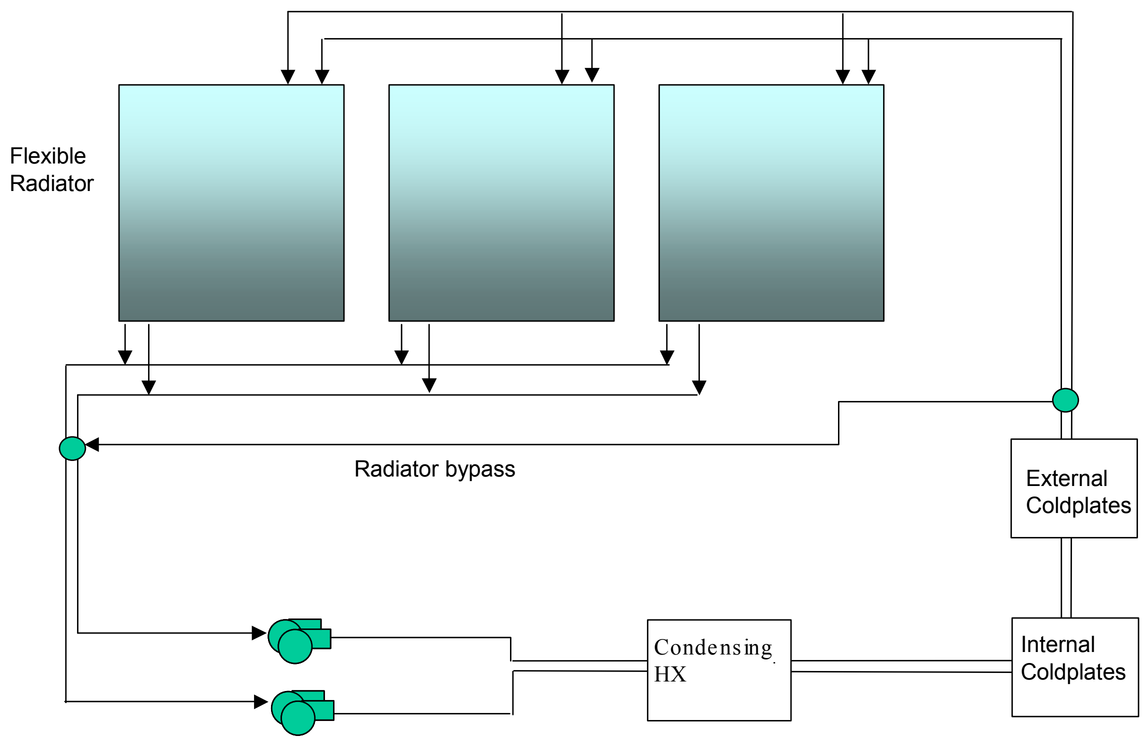


Figure 3.22 TCS Architecture Overview

of the radiator outlet temperature under varying heat loads and environmental conditions. The working fluid passes through the radiators to reject heat by radiant transfer to the exterior environment.

The TCS uses two independent fluid loops, each serving all heat acquisition devices and subsequently passing through the heat rejection equipment. Each loop is pressurized by an independent pump package. A pump package contains two identical pumps plumbed in parallel to provide one-fault redundancy per package. Overall, this loop architecture ensures that the Gateway has active cooling until all four pumps fail. As designed, the fluid loops operate at an average temperature of 288.9 K with an outlet set temperature of 275.0 K. The average radiator surface temperature is 286.8 K.

Figure 3.22 illustrates the single-phase, pumped fluid loop architecture chosen for the Gateway thermal control system.

As the TCS fluid loops operate with a single-phase working fluid, the working fluid temperature rises as it passes through each heat acquisition device. To mitigate the possibility of cooling sensitive equipment below the dew point of the surrounding atmosphere, thereby allowing condensate to form on the components, heat acquisition devices serving water-sensitive components are placed after the cabin heat exchangers in the flow loop. Therefore, a requirement to avoid thermal conditions within the pressurized volume that allow condensation formation places additional demands on the flow loop operating temperatures.

As such, the values here are representative and may change if additional analysis predicts condensation on electronics with the current TCS flow loop set point. Larger vehicles generally avoid the issue of cooling electronics below the atmospheric dew point by using two thermal control loops. In such an architecture, the condensing heat exchanger is served by the low-temperature TCS loop whose set point is below the cabin dew point to allow removal of latent thermal loads. The electronics, however, are served by the moderate temperature loop whose set point is above the atmospheric dew point. For the Gateway, this architecture is expensive in terms of mass and likely unnecessary.

The major thermal control system components for Gateway are summarized in Table 3.16.

Gateway TCS			
Component	**Mass**	**Volume**	**TRL**
Accumulators	3	0.026	9
Tubing/Piping	11	0.004	9
Heat Exchangers	19	0.024	9
Coldplates	86	0.200	9
Radiators	161	0.573	4
Pumps	13	0.009	9
TCS Working Fluid	115	-	5
Flow Meters	-	-	9
Valves	-	-	9
Shell Heaters	1	-	9
MLI	256	2.560	9
Total	**664 kg**	**3.4 m^3**	

Table 3.16 TCS Component Summary

Other TCS components are sized to provide redundancy under fault conditions. As noted earlier, loss of one complete radiator panel will still allow rejection of 67% of the nominal design heat load when the radiators face deep space. The flexible radiator panels are mounted to the inflatable portion of the Gateway, and will be packaged and folded with the inflatable fabric for launch. Due to the smaller inflatable shell size of the Gateway as compared to other proposed inflatable spacecraft such as TransHab, these radiator panels will not lay flat against the surface, rather will have to be attached at a point tangent to the inflatable section. The details of this attachment are not addressed here and are left for a future study.

Since the Gateway operating pressure has been baselined at 62.0 kPa (9.0 psia), equipment that depends upon internally mounted fans or fan and heat exchanger combinations must be sized to reject the same amount of heat at the lower operating pressure. This will be addressed by the individual components as part of the design process. In addition, the ECLSS air circulation fans and heat exchangers must be oversized to collect and distribute the same amount of heat as equipment sized for standard atmosphere (101.35 kPa) operation.

There were two sets of heaters sized for the thermal control system. The first set is associated with activation of Gateway upon initial inflation. Analysis performed for the TransHab inflatable module intended for ISS indicated that after the inflation sequence was competed, the air inside would be too cold for crewmembers to enter. With little equipment activated at that time there was not sufficient waste heat generated to warm the air in an acceptable time frame. Therefore, the TransHab design added heaters within the air distribution system to increase air temperature.

As a conservative measure, a placeholder for air activation heaters was included in the L_1 Gateway design. Whether these heaters are needed will depend upon actual activation timelines and heat load profiles, however this issue will be addressed in future studies. The second set of heaters included is required for the core pressure shell to prevent condensation from forming on the inner wall. An additional possible use is during launch and activation in order to insure adequate atmospheric temperature.

3.2.10.4 Technology Needs and Design Challenges

In the design above, most of the assumed heat transfer physics and equipment are flight-proven. The radiators are flexible metal weave or fabric body-mounted designs with an internal freeze-tolerant architecture. Radiators of similar design are currently being tested at the Crew and Thermal Systems Division of JSC and are currently at a TRL between four and five. Freeze-tolerance implies that the radiators may freeze and thaw as necessary to support spacecraft heat loads. This concept has a TRL of roughly four. The proposed working fluid, 60% propylene glycol with 40% water, has a TRL of five, though planned near-term testing should raise this to a TRL 6. Finally, other components identified have actual flight legacy and thus are at a TRL of nine.

Inflatable modules pose their own unique problems from a thermal control standpoint. The problem of maintaining adequate inner wall temperatures without the use of strip heaters during nominal operations has been discussed. Another design challenge is that during launch and prior to inflation, the interior of the module must be vented to space. This requires that all equipment within the inflatable section must withstand the vacuum of space and then function once the module is inflated. Some equipment may need to operate during this vacuum period, therefore would require some type of passive cooling that does not include air flow or liquid cooling via coldplates. Designing and certifying equipment to operate in a vacuum may add significantly to the overall cost. Rather, it would be beneficial to package as much equipment as possible in a section of the Gateway that remains pressurized throughout all mission phases.

3.3 References

[1] Schmitz, P. (2001). NASA Glenn Research Center, Personal Communication.

[2] McLallin, K. (2001). NASA Glenn Research Center, Personal Communication.

[3] Cerimele, M., et al. (1992). Proposed Standards for Human-Rating Space Systems, JSC-23211. NASA Johnson Space Center. Houston, TX.

[4] National Aeronautics and Space Administration. (1998). Human Ratings Requirements, JSC-28354. NASA Johnson Space Center. Houston, TX.

[5] National Aeronautics and Space Administration. (2001). Individual Crew Quarters Design Requirements, Manned Systems Integration Standards (NASA STD 3000), Section 10.4.3.f.2.

[6] National Aeronautics and Space Administration. (2001). Body Envelope Design Considerations, Manned Systems Integration Standards (NASA STD 3000), Section 8.6.2.3, Figure 8.6.2.3-1.

[7] Hoffman, D. (1993). Station-keeping at the Collinear Equilibrium Points of the Earth-Moon System. NASA Johnson Space Center. Houston, TX.

[8] Schoppa, W. (1997). ITCS Fluids White Paper, HDID-A44B-827. Lockheed Martin Mission Systems and Services. Houston, TX.

4.0 Safety, Reliability, and Sparing Analysis

4.1 Introduction

Safety, Reliability & Quality Assurance's (SR&QA) early involvement in the Gateway design process began with the following guidelines and products:

- The establishment of prioritized safety and reliability guidelines to assure crew and vehicle safety should include the following in designing for minimum risk:
  - Design out hazards where possible;
  - Known hazards that cannot be eliminated by design will be reduced to an acceptable level by incorporating hazard controls into the system design;
  - When it is impossible to preclude the existence of known hazards, detection systems shall be used to provide timely warning of the ensuing hazardous conditions;
  - Special procedures shall be developed to counter hazardous conditions when it is not possible to reduce the magnitude of a potential hazard by design.
- The identification, tracking and documentation of hazards to crew and vehicle safety through a Preliminary Hazard Analysis (PHA)
- The performance of system reliability and availability analyses that predict logistics support levels and mission success probabilities using various tools.

SR&QA provides the design team with a more comprehensive understanding of the risk involved with conducting the planned missions. This is accomplished by employing qualitative and quantitative risk assessment methodologies for the management of risk to the program (i.e. a Risk List, Probabilistic Risk Assessment). Furthermore, once a program is established, it will lead to a better definition of mission requirements.

SR&QA support focused on four major areas to help make early safety, reliability, mission architecture, and element design decisions. The first major area of support is the daily presence of an SR&QA representative during team meetings. This helps provide safety and reliability insight to the subsystem design engineers who incorporate these engineering disciplines into the design and operations of the planned mission. For the second major area of support, a PHA is generated to identify aspects of the design and architecture that contain the most risk to the crew and vehicle. It also documents design controls to mitigate each specific risk. In the third major area of support, reliability, fault tree, and availability modeling of the critical subsystems comprising the elements were completed. The completed models show the benefits of adding functional redundancy providing a best estimate of maintenance and sparing requirements, and can quantify areas of high risk helping team leads make more informed decisions. Finally, a risk list is documented in the Continuous Risk Management (CRM) process focusing on program and project risks for the team's managers and leads to efficiently improve the design cycle process. From these types of analyses, recommendations are incorporated into the design process and mission architecture that positively affect the team's communication, hardware design, and operating scenarios in terms of risk abatement.

4.2 Scope

The scope of the reliability/risk analyses is to present results generated from the aforementioned types of analyses for the Gateway. Quantitative results of mission success, availability, and spares requirements are based on fault tree and Reliability Block Diagram (RBD) models of the Gateway subsystems derived in cooperation with the participating subsystem engineering leads. These models are based on one complete Gateway mission. Qualitative safety analysis is based on a generic set of hazardous conditions typically encountered in human space flight and the design, operations, elements, and systems that are part the Gateway mission.

4.3 Analysis Methodologies

4.3.1 Quantitative Analysis Methodologies

4.3.1.1 Probabilistic Risk Assessment (PRA)

PRA is a general term given to quantitative methodologies that assess risk. A mission to be assessed and its success criteria are defined, then, elements of the mission subject to failure are identified and modeled in various ways. The following two techniques are used in support of Team Expo to predict mission success, subsystem sparing requirements, and reliability: Reliability Block Diagrams, and Fault Trees.

RBD and Fault Tree models are produced to do the reliability and availability analyses and are based on concepts generated by the team's subsystem leads. RBDs and Fault Trees represent the functional relationship and interdependencies between components in a system. RBD models are developed in success space using various combinations of serial or parallel logic that define the success criteria of the system. Fault Tree models are developed in failure space and model the likelihood of failure of a given system architecture. Both techniques can be used to predict the reliability of a system. To develop the models with a high fidelity, subsystem data residing in the engineer's concept templates and their corresponding schematics are used as a first cut at the subsystem architecture. Once the RBD and Fault Tree models are developed, they are reviewed to end any questions or issues about the logic presented and to gather more information about the repairability of the subsystems. Overall, these two techniques make up the basis of what constitutes a quantitative system analysis.

4.3.1.2 Quantitative Analysis Tools

Once a final RBD or Fault Tree is established, the data is input in selected software tools to quantify the results. The following software tools are used to generate the predictions from the RBD and Fault Tree models.

System Analysis Programs for Hands-On Integrated Reliability Evaluation (SAPHIRE) is the software tool used to construct subsystem Fault Trees. Each event in the Fault Tree represents a component in a subsystem and has an appropriate probability of failure over the mission time. SAPHIRE will calculate the subsystem failure probability and generate cut sets which can be used to aid in designing to a given reliability allocation.

Rapid Availability Prototyping for Testing Operational Readiness (RAPTOR) software is used to simulate an RBD model's reliability and availability. This software randomly schedules failures of all the parts in a system, in accordance with their failure rate and averages the results over a number of iterations. A Monte Carlo process is used to calculate the following results: subsystem availability, maintenance downtime, and all failed parts.

Sparing Analysis Software (SPARAS) was developed by SR&QA to do data analysis on the "all failed parts" output files from a RAPTOR or Object-Oriented Simulation of Maintenance and Operations for Space Systems (OSMOSSYS) simulation. SPARAS reads RAPTOR or OSMOSSYS output files and calculates the number of spares required to achieve a given sparing confidence level.

4.3.1.3 Assumptions Used in Quantitative Predictions

Some assumptions regarding input data must be made to do quantitative reliability and availability prediction analyses. The most important and consequential assumption is the failure rate data. To get a good first set of failure rate data for the parts used in modeling the subsystems of the current study, historical data from similar systems in past and current NASA, commercial satellite, and military programs are used. In addition, the failure rate for all parts in the modeling completed for the Gateway design is assumed constant. Therefore, infant mortality and wear out are not included in the models. Preventive maintenance or sparing for consumables, such as the vent loop filters, is also not included. Furthermore, the Mean Time to Repair (MTTR) and repairability data were based on subsystem engineering experience and therefore assumed since these are application specific. As with any modeling activity, these assumptions contribute a certain amount of uncertainty in the results. Therefore, the results presented are not perfectly representative of actual conditions, but can provide an estimate of system performance enabling trade studies and sensitivity analyses to contribute positively in the element designs.

4.3.2 Qualitative Analysis Methodologies

4.3.2.1 Preliminary Hazard Analysis

The purpose of the Preliminary Hazard Analysis (PHA) is to identify safety-critical areas, to identify and evaluate hazards, and to identify the safety design and operations requirements needed in the program concept phase. The PHA provides management with knowledge of potential risks for alternative concepts during feasibility studies and program definition activities.

The PHA conducted is continuously updated as the design progresses and is posted on the Exploration Office website. Where subsystem design has a high level of risk or doesn't meet human ratings requirements, actions are tracked until adequate controls are put in place.

4.3.2.2 Risk List

The purpose of the risk list is to identify and track program and process risks which can be prioritized and appropriately mitigated. It results in the following benefits:

- Enhances confidence in decision making
- Early identification of potential problems
- Increase chance of the project success
- Enable more efficient use of resources
- Promote teamwork by involving personnel at all levels of the project

- Collection of information for trade-offs based on priorities and quantified assessment

4.4 Gateway Results

4.4.1 Gateway Success Probability and Sparing Results

Success Probability results for each of the studied subsystems making up the Gateway is presented in Figure 4.1. As seen in this chart, the Electrical Power System (EPS), Environment Control & Life Support System (ECLSS), and Avionics subsystems contribute most to the unreliability of the Gateway system. With spares and repair, these systems can attain a high level of success probability since all or the majority of parts composing them are repairable. Trade studies between reliability, maintainability with crew time availability could be done to select a final system design philosophy. The modeling techniques incorporated in this study contain the capabilities to help make these types of decisions and can result in selecting the optimum combination of features.

Figures B.1 through B.5 in Appendix B provide more detail about the sparing requirements for the Avionics, TCS, ECLSS, EPS, and EVA subsystems. These charts show the confidence that the selected number of spares allowed for that subsystem will meet its needs. For example, in Figure B-1, if twenty spare parts are carried for the avionics subsystem, there is approximately 99% confidence that the sparing needs during the mission of the avionics subsystem will be met. Likewise, there is approximately 3.4% confidence that the avionics subsystem will need zero spares. The sparing recommendations in these charts are based on maintaining the subsystem as modeled in top shape (all parts working) and do not necessarily contribute to the highest gain in subsystem

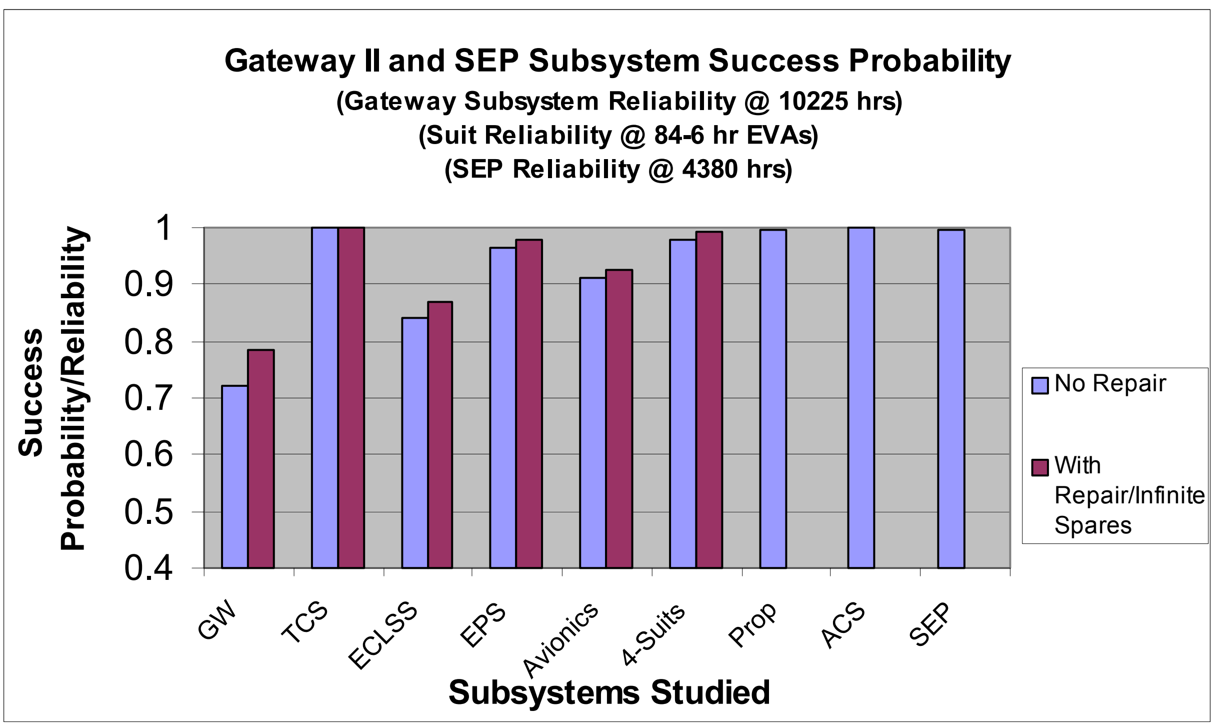


Figure 4.1 Gateway Success Probability

Avionics	ECLSS	EPS	TCS	EVA
Central Computer (3)	Remote Power Controller (10)	Sun Sensor (4)	Pump Package Assembly	EVA will achieve 95% confidence with zero spares
Remote Power Controller (6)	Oxygen Partial Pressure Sensor (9)	Gimbal Drive Unit (2)		
External Video Camera	Flow Control Valve	Sun Sensor Electronics (3)		
Inertial Navigation System	Water Delivery Valve	SAOS Power Supply Unit		
Caution & Warning Panel	Pressure Regulator	DC Switching Unit		
	Pressure Control Panel	SAOS Signal Processor		
	Smoke Detector	Battery Charge/Discharge Control Unit		
		Remote Power Controller		

( ) Numbers in parentheses represent quantity of components

Table 4.1 Gateway Cumulative LRU Sparing

probability of success. These charts may be used for selecting spares for the subsystems given a sparing confidence goal. However, sparing selection and subsystem configurations should be based on an optimal mix of what leads to the highest subsystem probability of success, the lowest mass requirement, and the least maintenance demand. An optimal balance could be obtained with further, more detailed studies and interactions with the subsystem team leads.

Listed in Table 4.1 is a sparing list for each of the subsystems studied in Figures B.1 through B.5. This list ranks in priority the spares that should be brought for each subsystem at the 95% confidence level. This table represents a sample-sparing list for the Gateway mission. Spares selected are based on the parts that are most likely to fail regardless of whether those failures contribute to system down time. The spares list below is not optimized to probability of success or mass but is simply the parts required to keep the system in top shape. More iterations on subsystem design, redundancy configuration and crew time availability for maintenance need to be studied to attain an optimal sparing list. (It should be noted however, that there is a 99.99% probability that if all spares are allowed at 100% confidence, the EPS, Avionic, TCS, EVA and ECLSS subsystems could attain the projected probability of success, "with repair," listed in Figures B.1 – B.5).

4.4.2 Gateway Risk List

Shown in Table 4.2 is the prioritized Risk List generated for the entire Gateway design study. This list details the top twenty-two risks (based on a subsystem ranking) for the Gateway study. The subsystem engineers perceive these top risks from their respective subsystem. The complete Risk List will be produced in accordance with the CRM process and is used to identify and document risks through the lifecycle the study. Generation of the Risk List is the first step in the CRM process. The Gateway project managers will continue to evaluate risks and make recommendations to the team on effective action plans.

Table 4.2 Gateway Risk List

RISK #	RISK STATEMENT	INITIATOR
GW-01	Mission scenarios for space-based telescopes are not well defined by the customer; there is a possibility that the Gateway feasibility assessments will not consider all requirements.	Element Lead
GW-02	Failure to design systems to two-fault tolerances may result in critical systems failures.	Element Lead
GW-03	A computer systems failure (hardware or software) may result in being unable to monitor and control the Gateway systems.	Avionics
GW-04	A failure during the unmanned phases may result in being unable to communicate with Earth or visiting vehicles.	Avionics
GW-05	Given an ECLSS system failure, there is a possibility of loss of atmosphere in the Gateway.	ECLSS
GW-06	If there is a toxic chemical release or potable water contamination in the cabin, it may result in crew health degradation or crew loss.	ECLSS
GW-07	EVA suit failure may lead to loss of EVA capability, loss of crewmember or mission failure.	EVA
GW-08	If element interfaces are not constant across the architecture, this could lead to increased program costs.	EVA
GW-09	A lack of logistics Resupply plan may result in inadequate consumables on the Gateway leading to mission failure.	Mission Operations
GW-10	If there is no requirement for the Gateway LEO checkout, systems may not function properly, leaving the Gateway inoperable.	Mission Operations

RISK #	RISK STATEMENT	INITIATOR
GW-11	Food preparation equipment failure may lead to insufficient nutrition.	HF&H
GW-12	Should there be a critical failure of the crew exercise equipment, it may lead to crew health degradation.	HF&H
GW-13	If the power system fails, providing insufficient power to crew systems, the mission may fail.	Power
GW-14	The Gateway solar arrays could be hit by orbiting debris; this may lead to insufficient power to send the Gateway to L1	Power
GW-15	If there is a failure of the SEP thruster, this may result in: 1) loss of attitude control, 2) inability to achieve lunar L1 orbit, or 3) loss of station-keeping at Lunar L1.	Propulsion
GW-16	If element interfaces are not constant across the architecture, this could lead to increased program costs.	Propulsion
GW-17	A critical failure of the robotics system may result in reduced EVA capacity and mission failure.	Robotics
GW-18	A failure of the dexterous robotic system (Robonaut) may result in the inability to perform automated external maintenance.	Robotics
GW-19	If there is a leak in the Gateway systems, it may require excessive station keeping, leading to xenon depletion.	Structures
GW-20	If an inflatable structure is used for the Gateway, there is little or nor data on long duration exposure for materials at or near lunar orbit; there may be premature degradation of polymer/composites could lead to early end of life or structural failure	Structures
GW-21	If the TCS radiators fail, they may not be able reject sufficient energy to space, leading to systems failure.	TCS
GW-22	A TCS heater failure may result in a systems failure due to exceeding lower or upper temperature limits.	TCS

4.4.3 Gateway Preliminary Hazard Analysis

Shown in Table B.1 is the PHA conducted for the manned phase of the Gateway mission. This analysis documents both generic and unique operations, hazardous conditions, and their "worst case" effects and controls. Controls listed reflect the current Gateway element designs and operating scenarios as outlined by the Design Team. Overall, seventy-nine hazardous conditions causes were identified, seventy-seven were identified and controlled, and two were open. Currently there are zero accepted risks based on the crew's ability to utilize the Crew Transfer Vehicle (CTV) for return/escape capabilities. Open work from the Hazard Analysis includes a recommendation that an analysis of the radiation protection for the Gateway's final configuration be performed. This will affect the hazard controls for the two conditions identified concerning excessive radiation in the crew habitable environment.

Table B.1 is found in Appendix B.

4.5 Gateway Subsystem Findings

Attitude Control System: The ACS of the Gateway has a base reliability of 99.9% with no repair. The ACS consists of five flywheels and five power generators. There is no sparing analysis done on the system due to the fact it is non-repairable on orbit.

Avionics: The Avionics subsystem as configured by the subsystem designers for the Gateway has a base reliability of 91.3% with no repair. A high probability of mission success may be obtained by bringing spares for this subsystem in accordance with the RAPTOR sparing analysis. The highest contributors to the unreliability of the Avionics subsystem are the video tape recorder, video monitor, and the central computer.

ECLSS: The ECLSS as configured by the subsystems designers for the Gateway has a base reliability of 84.0%. Since nearly all parts of this subsystem were assumed repairable, a high probability of success could be attained if one allows all potential spares to be brought, as predicted from the RAPTOR sparing analysis. The highest contributors to the base unreliability are the cabin condensate water separator, water delivery valve, and the water tank. These three components are modeled as being single string. Concentration on redundancy in this area is recommended to increase the base reliability for the system as modeled.

EPS: The EPS, with the redundancy contained in the Gateway, has a base reliability of 96.5% with no repair. This base probability of success will improve if all potential spares for this subsystem, in accordance with the RAPTOR sparing analysis, are allowed. One way to increase the base reliability of the EPS is to increase redundancy for the sun sensor electronics, which control the solar arrays orientation, and the sun sensors. Improving upon the deployment of the solar arrays and the deployment of the truss to which the solar arrays are mounted to, will also increase the base reliability of the EPS.

EVA: The EVA suit has a base reliability of 99.5% with no repair. However, the Gateway will require four EVA suits for mission operations. The base reliability of four EVA suits with no repair is 99.2%. The events that contribute most to the unreliability are the pump package assembly, the blower in the vent loop, and the UHF transceiver. Adding the necessary redundancy to the EVA suit will increase the overall base reliability.

Propulsion: The Gateway Propulsion subsystem has a base reliability of 99.5% with no repair. The events that contribute most to the Propulsion system's unreliability are the tank burst discs. There is no sparing analysis done on the system due to the fact it is non-repairable on orbit.

TCS: The TCS subsystem has a base reliability of 99.9% with no repair. The events that contribute most to the unreliability in the system are the pump package assemblies. A higher probability of mission success may be obtained by bringing spares for this subsystem in accordance with the RAPTOR sparing analysis.

SEP: The SEP has a base reliability of 99.7% with no repair. This base reliability was not included in the overall Gateway probability of success. There was no sparing analysis done on the system due to the fact it is non-repairable on orbit.

4.6 Conclusions

Further iterations on these concept subsystems for the Gateway are needed to provide insight into the redundancy levels required to achieve a high rate of mission success. This iterative process is required to achieve an optimum balance of system redundancy, sparing levels, and maintenance demand that contribute to the lowest mass and highest probability of mission success. The modeling techniques incorporated in this study contain the capabilities to help make these types of decisions and can result in selecting the optimum combination of design features. These features should maximize mission success, reduce risk to the crew, and help achieve a lower life cycle cost.

5.0 Summary

5.1 Technology Assessment

A primary design goal of the L_1 Gateway is to utilize and demonstrate advanced system technologies where prudent. As a result, significant technology development investments will be required to bring the design to flight-ready status. This section examines some of the more pressing technology needs and their impact on the overall Gateway design.

Structures: Inflatable structures may prove valuable for future exploration by reducing mass and packaging volume while providing large crew volumes. The Gateway inflatable section design draws upon knowledge gained during NASA's TransHab project, a proposed habitation module for the International Space Station. However, development efforts are still required to prove their performance in the space environment, as well as long-duration exposure degradation data to understand the deleterious effects of radiation. An open issue in the Gateway design is the behavior of soft goods over many years in the radiation-heavy environment of Lunar L_1. Nonetheless, inflatable systems may be extremely beneficial for both zero-g and planetary surface applications, and should be pursued further.

Also needed for the Gateway and human space exploration in general are revolutionary approaches to providing radiation shielding. The typical methods for satisfying this are passive systems consisting of layers of hydrogen-rich materials such as water or polyethylene. Studies should be performed to understand the optimal material set for this function and how the selected material can be used to provide additional functionality to the spacecraft. Another approach to radiation protection is active shielding techniques. These promise tremendous mass savings over passive systems, however are currently at very low technology levels. To raise this technology to an appropriate level, significant efforts will be required but may prove extremely rewarding.

ECLSS: Closed-loop life support is needed for long-duration human exploration to significantly reduce the consumables required to support the crew. Though the Gateway is uninhabited for much of its lifetime, ECLSS components for recycling air and water have been selected to minimize initial launch mass and subsequent resupply. Several of these systems are being developed for the International Space Station, yet considerable technology development work is still required to bring the overall ECLSS concept to flight-ready status. Specific areas of need include atmosphere revitalization, water reclamation, and waste processing.

Avionics: A number of advances in avionics technologies are possible focusing on reducing mass, power, and volume required for these systems. Micro- and nano-scale technologies may not have a tremendous impact on the total mass of a spacecraft, but may have important ancillary benefits such as risk reduction through redundancy by providing 10's or 100's of similar components. The high bandwidth requirements of long-distance communication may be met with inflatable antenna technologies. These structures offer mass and packaging savings over traditional rigid systems. Another potential area is wireless transmission of power and data, which may provide important mass reduction benefits, as wiring typically comprises a large portion of the overall power and avionics systems. Fortunately, most of these technologies are being developed for industrial application, however technology development will be required to provide their operation in space-based applications such as the Gateway.

Robotics: Robonaut, a small, dexterous robot, may assist humans by performing repetitive EVA tasks and remote operation/maintenance of spacecraft systems. When the Gateway is unstaffed, an on-board Robonaut system may be used to perform both internal and external spacecraft maintenance tasks. These partners also offer the potential for manual dexterity equal to that EVA crewmember without putting the human operator in a hazardous environment. Such capabilities for assisting humans may be necessary in the complex task of assembling large gossamer telescopes on-orbit. Technology development efforts for dexterous robots should focus on increasing mobility, autonomy, and telepresence capability.

EVA: Inflatable airlocks can provide routine EVA capability and atmosphere reclamation while reducing volume and mass requirements. For the Gateway, 85% of the airlock atmosphere will be recovered per airlock cycle, which results in considerable consumable mass savings when integrated over the 2-year resupply period. Technology work is necessary to develop the flexible structure of this particular airlock concept, however experience gained in inflatable systems can be drawn upon to quickly raise its technology readiness level. Other investments in the EVA discipline involve advanced space suit development. For future planetary exploration, advances in EVA technologies are needed for mobile, dexterous operations. The current space suit design used for EVA from the Shuttle and ISS, the extravehicular mobility unit (EMU), is unsuitable for surface exploration. Therefore, in looking forward to future needs, suit designs for lunar and eventually martian surface exploration are used at the Gateway.

Power Systems: Advances in photovoltaic cells promise increased radiation hardness, efficient packaging, lower mass, and greater conversion efficiencies. Human exploration missions will require high power generation for complex systems. Dedicated energy storage technologies such as thin film Lithium-Ion batteries are also needed for meeting the significant power requirements of HEDS applications. That need is clearly illustrated in the Gateway design and its large energy storage requirement. However, a potential revolutionary concept has been identified in which the structure of the battery contributes to the overall structural content of Gateway, thus enabling tremendous mass savings. Technology development is needed to demonstrate the applicability of this concept to the Gateway mission.

Related to the power system technology development need identified above are integrated attitude control and energy storage devices such as mechanical flywheels. This system, implemented in the Gateway design, shares a significant energy storage burden with and provides a backup to the primary batteries while handling the attitude control needs. The advantage of such an approach is mass savings from a reduction in hardware required, therefore also minimizes complexity. Integrated power and attitude control has not yet been demonstrated in a laboratory environment on development hardware, therefore technology work is required.

TCS: Efficient thermal radiators are needed to reject heat from high power, large volume exploration spacecraft. Flexible radiators offer mass reduction and increased placement options, as witnessed by the body-mounted configuration selected for the Gateway inflatable section. Technology development for these systems is underway at NASA's Johnson Space Center with promising results achieved, however additional work is necessary for fully assessing their applicability.

Propulsion: A pressing need for not just the Gateway but also all human exploration spacecraft is a low mass, power-efficient cryocooler. These missions require large stores of fluids to be stored at cryogenic temperatures for long durations in order to minimize mass and volume.

5.2 Open Issues and Forward Work

Despite the level of detail achieved for this design iteration of the Gateway, a few unresolved issues remain to complete the initial study. Protection from the detrimental effects of solar particle and galactic cosmic ray radiation is a necessary component of any human exploration spacecraft, particularly beyond Low Earth Orbit. However, due to time constraints and lack of design resources, the current Gateway configuration at the time of this writing does not include any dedicated active or passive shielding systems. Work is presently underway to consider this problem and will be incorporated as it becomes available.

Another item requiring resolution is the effect that long-duration radiation exposure will have on the Gateway structure and subsystems. Recall that the Gateway is delivered from LEO to Lunar L_1 via a low-thrust Solar Electric Propulsion Stage. This entails multiple spirals through the Van Allen radiation belts and their associated high-energy trapped particles. In addition, the Gateway will remain on-orbit at the Lagrange point for fifteen years. As this location is beyond the protection of Earth's magnetosphere, it is constantly bombarded with solar particles, GCRs, and ultraviolet and X-ray electromagnetic radiation. This harmful radiation causes electronic component malfunctions, breaking of long polymer chains such as those found in the Gateway inflatable structure, and many other undesired effects. While these effects are fairly well understood and can be experimentally verified in a laboratory environment, they have not been applied to the Gateway design. First, however, a complete characterization of the operating environment from launch to end-of-life must be performed.

A number of other less obvious yet critically important open issues must also be considered as the Gateway design evolves. These items, such as assessing the torque disturbance environment and Gateway trash disposal plan, are outlined in the subsystem design sections.

For future iterations of the Gateway, several unknown matters and assumptions made for this study should be re-evaluated. Presently, a reference design for a Gateway resupply vehicle has not been submitted. The resupply requirements generated from this study though can be used to feed initial requirements for the vehicle. Having a reference, the cost and operational impact of the 2-year Gateway resupply assumption can be examined and adjusted accordingly. The Gateway design will then be iterated upon to incorporate any new architecture baseline.

Though a full complement of EVA and robotics capabilities have been added to this study of the Gateway, certain assumptions were made in order to press ahead with the design. At this time, a detailed assembly sequence for the FAIR telescope and accompanying vehicle support requirements are unavailable, as well as a satisfactory baseline for mission duration and mission frequency over the lifetime of the Gateway. The assumptions made regarding telescope matters may have a profound impact on system design, resupply requirements, and spacecraft configuration. These must be closely scrutinized to understand their sensitivities. Work is currently underway to devise an appropriate assembly sequence and support needs for the telescope, and when complete, the results of this study can be folded into the Gateway design.

Another area for future study is a detailed study of the dynamic effects on a stationed spacecraft at Lunar L_1. Though NASA previously has encountered and orbited equilibrium points, the Lunar L_1 point has never been visited, much less attempted to position a spacecraft precisely at the point. Analytical studies have been performed, nonetheless, to investigate the station-keeping requirements for such an application. While these studies have generated very promising results, most have failed to fully incorporate all dynamical effects or have made certain assumptions unsuitable for "real" spacecraft. The Gateway design has taken a conservative approach for the station-keeping system that is appropriate for a first iteration on a study, however a detailed assessment may significantly ease this requirement. This will have a major impact on subsequent system sizing and resupply needs.

Finally, a potential item for future study is to examine the benefits of inflatable structures for human exploration applications. The Advanced Design Team was asked to incorporate inflatable technologies for this attempt at the Gateway design. It was quickly determined, though, that a hybrid configuration was necessary to fully meet the subsystem needs. As the final pressurized volume of the hybrid Gateway is nearly identical to that predicted for a rigid structure design, a trade can be performed to examine the impact of this decision. The benefits of inflatable systems for human exploration may then be measured by traditional metrics and less quantifiable factors such as risk, habitability, and applicability to alternate implementations.

5.3 Conclusion

The Lunar L_1 Gateway is a unique concept for expanding human infrastructure beyond Low Earth Orbit while providing a wide range of functionality. As the centerpiece of the Gateway Architecture, it is designed to host a suite of missions, from lunar surface expeditions to large telescope assembly and servicing. The spacecraft configuration and subsystem concepts outlined in this report represent one technologically advanced, technically feasible solution, however matters unresolved from this study and left as future work must be addressed as this design matures. Nevertheless, future studies should be performed to examine different approaches to the same design with a goal of minimizing cost while increasing functionality.

Appendix A

Requirements, Constraints, and Design Goals

Requirements

1.0 Top Level Architecture Requirements

1.1 Stage Lunar surface excursion, telescope construction and servicing, and cargo depot missions through the L_1 Gateway located at Lunar L_1
Rationale: This is from the definition of the Gateway architecture. Lunar L_1 is used to enable short transfer times to the lunar surface, and inexpensive invariant manifold transfers to Earth L_2.

1.2 The L_1 Gateway shall be capable of performing scientific investigations
Rationale: The L_1 Gateway will meet the scientific objectives laid out in TBD (A document to be written - Dr. Harley Thronson/HQ).

1.3 The L_1 Gateway shall have a design lifetime of 15 years
Rationale: A single L_1 Gateway will be used for the entire program. The large complex science facilities program requires 15-year support from the L_1 Gateway.

1.4 The L_1 Gateway shall support a crew of four
Rationale: Lunar surface missions and other activities require EVA pairs, which is a general philosophy for EVAs. This requirement is common to the entire Gateway architecture.

1.4.1 Support crew for 35-day telescope construction missions
Rationale: 25-day missions are required for L_1 Gateway telescope construction scenarios, with 35-day stays baselined to cover a missed departure opportunity.

1.4.2 Support crew for 22-day stays in the L_1 Gateway for lunar surface missions
Rationale: Three-day lunar surface missions require up to 9.5-day stays at the L_1 Gateway, with 20-day stays baselined to cover a missed departure opportunity. Thirty-day lunar surface missions require up to 22-day stays at the L_1 Gateway to cover a missed departure opportunity.

1.4.3 Support two telescope construction or servicing missions per year for program lifetime
Rationale: The Gateway Architecture baselines four CTV missions per year, with two missions dedicated to lunar surface excursions, and two missions for telescope construction or servicing.

1.4.4 Support two lunar surface missions per year for program lifetime
Rationale: The Gateway architecture calls for two surface missions per year.

1.5 The L_1 Gateway shall use existing launch vehicle infrastructure for all launch support
Rationale: A Gateway architecture restraint. This includes launch vehicles currently operating or planned with an expectation that they will be at TRL 6 by 2005.

1.6 The L_1 Gateway position shall be maintained at Lunar L_1 for entire L_1 Gateway lifetime following transit from low-Earth orbit
Rationale: Lunar L_1 is weakly unstable, thus requires position keeping over the lifetime of the architecture to maintain itself at the libration point.

1.7 The L_1 Gateway shall be autonomously transferred from Low Earth Orbit to Lunar L_1
Rationale: The L_1 Gateway will be unmanned during its transit to Lunar L_1. Delivery via solar electric propulsion will be baselined for initial study.

1.8 The L_1 Gateway shall provide capability for remote command and control of L_1 Gateway systems from Earth and visiting vehicles
Rationale: The L_1 Gateway will not be permanently inhabited, thus requires remote system tele-operation prior to crew arrival.

1.9 The L_1 Gateway shall provide capability for tele-operation of remote systems from the L_1 Gateway
Rationale: Robotic systems used in telescope construction will be tele-operated.

2.0 Logistical Requirements

2.1 The L_1 Gateway shall be capable of simultaneously supporting three vehicles set in a dormant operating mode while docked to the L_1 Gateway using Gateway resources
Rationale: CTV, Lunar Lander, and Logistics/Cargo Transport module docked during lunar mission.

2.2 The L_1 Gateway shall provide two-person EVA capability for nominal operations
Rationale: Nominal EVAs required for telescope construction and spacecraft maintenance operations. Advanced robotic partners will provide additional capabilities.

2.3 The L_1 Gateway shall provide external payload restraint and manipulation capability
Rationale: This is required for telescope construction & servicing and spacecraft maintenance.

3.0 Safety and Compatibility Requirements

3.1 The L_1 Gateway shall protect the crew and spacecraft against natural and induced operating environments
Rationale: Human Space Flight Requirement. Operating environments include launch from Earth, Low Earth Orbit, transit to Lunar L_1, and on-orbit at Lunar L_1.

> 3.1.1 The Gateway shall provide radiation protection against Solar Particle Events (SPE) and Galactic Cosmic Rays (GCR) to a probability of TBD% of not developing fatal cancer
> *Rationale: Human Space Flight Requirement. Maximum allowable radiation dosage is TBD rem/year.*

3.1.2 The L_1 Gateway shall be capable of withstanding launch loading
Rationale: Human Space Flight Requirement.

3.1.3 The L_1 Gateway shall protect the crew and spacecraft from micrometeoroid and orbital debris (MM/OD) to a 0.95 probability of no penetration
Rationale: This is the probability that the project managers are willing to accept.

3.2 The L_1 Gateway shall operate at a maximum cabin pressure of 70.3 kPa (10.2 psi)
Rationale: The pressure was chosen to minimize pre-breathe time before EVAs and to reduce structural requirements. This pressure enables commonality with other Gateway architecture elements. Lower operating pressures are possible with higher oxygen partial pressure fractions.

3.3 The L_1 Gateway shall provide a structural, power, and data transfer interface with the Solar Electric Propulsion Stage
Rationale: SEP is baselined for the initial L_1 Gateway study.

Constraints

1.1 Use inflatable technology for the primary L_1 Gateway structure
Rationale: The use of an inflatable structure is a constraint levied upon the team for the first study of the L_1 Gateway. The L_1 Gateway will be used as a technology test bed for future human space exploration.

1.2 Two-launch maximum for delivering the L_1 Gateway and SEP to Low Earth Orbit
Rationale: The L_1 Gateway and SEP stage should require no more than one launch each to deliver from ground to Low Earth Orbit.

1.3 The Gateway shall be delivered from Low Earth Orbit to Lunar L_1 via solar electric propulsion
Rationale: SEP is baselined for the initial L_1 Gateway study.

Design Goals

1.0 Safety, Reliability, & Operability

1.1 Crew safety is highest priority
Rationale: Philosophy of all Human Space Flight designs.

1.2 Use non-toxic fluids in L_1 Gateway systems
Rationale: Satisfy crew safety concerns.

1.3 Minimize complexity
Rationale: Satisfy crew operability and maintainability issues.

1.4 Maximize reliability
Rationale: Satisfy crew operability and maintainability issues.

1.5 Maximize maintainability
Rationale: Satisfy crew operability and maintainability issues.

1.6 Design for optimum crew use and operations
Rationale: Satisfy crew operability and maintainability issues.

1.7 Design to be ground processing friendly
Rationale: The L_1 Gateway will be processed prior to launch, therefore must be able to be thoroughly inspected.

1.8 Design for automated checkout in ground processing
Rationale: The L_1 Gateway will be processed prior to launch, therefore must be able to be thoroughly inspected.

1.9 Maximize system upgradeability (Line Replaceable Unit (LRU) Philosophy)
Rationale: The L_1 Gateway systems must be designed to be easily checked-out, repaired, and replaced.

2.0 Gateway Architecture Goals

2.1 Maximize system technology demonstration capability
Rationale: The L_1 Gateway will be used as a technology test bed for future human space exploration.

2.2 Maximize use of system technologies common to Mars program
Rationale: The L_1 Gateway will be used as a technology test bed for future human space exploration.

2.3 TRL 6 by 2005 for all systems technologies
Rationale: For flights by 2010, all technologies must be at TRL 6 five years prior to the first flight. However, some systems choices may be made for Mars technology development, therefore it is a soft requirement.

2.4 Minimize cost
Rationale: This is a Gateway Architecture goal.

2.5 Maximize science potential
Rationale: The L_1 Gateway presents a unique opportunity for performing in-space science; therefore it should be designed to maximize this potential.

2.6 Maximize commonality with existing architecture
Rationale: Common systems should be designed for all elements of the Gateway Architecture.

Appendix B

Safety, Reliability, and Sparing Analysis Figures

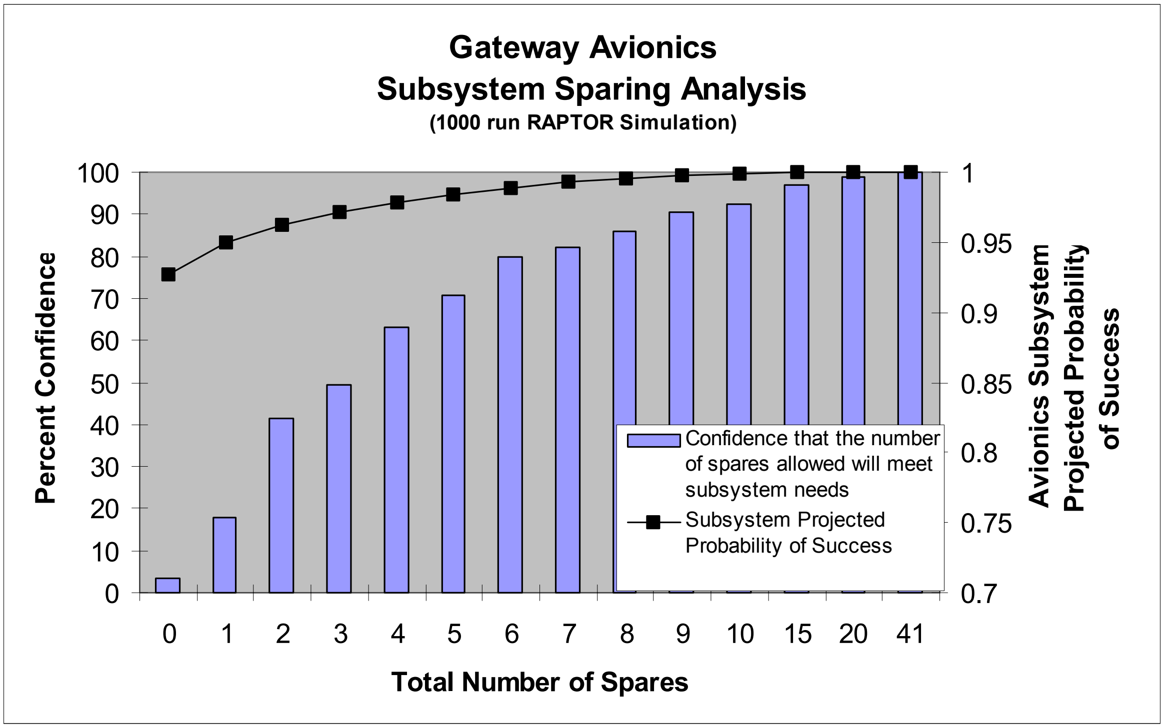


Figure B.1 Avionics Subsystem Sparing Results

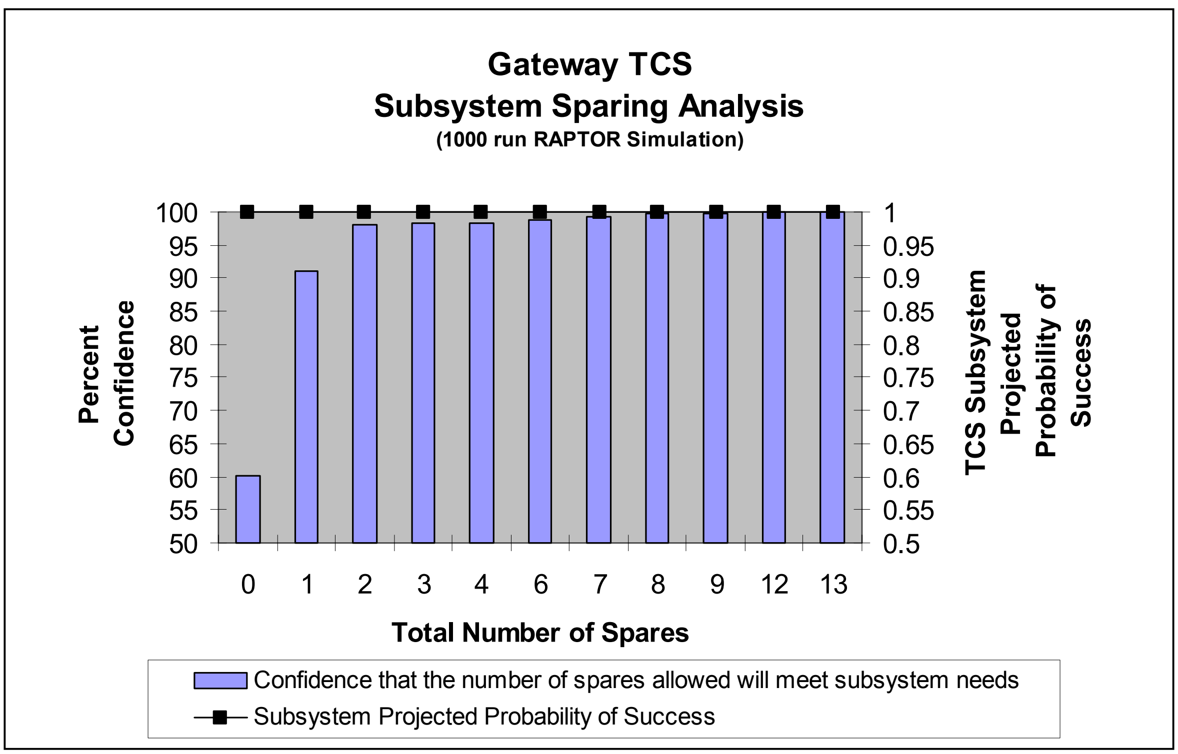


Figure B.2 TCS Sparing Results

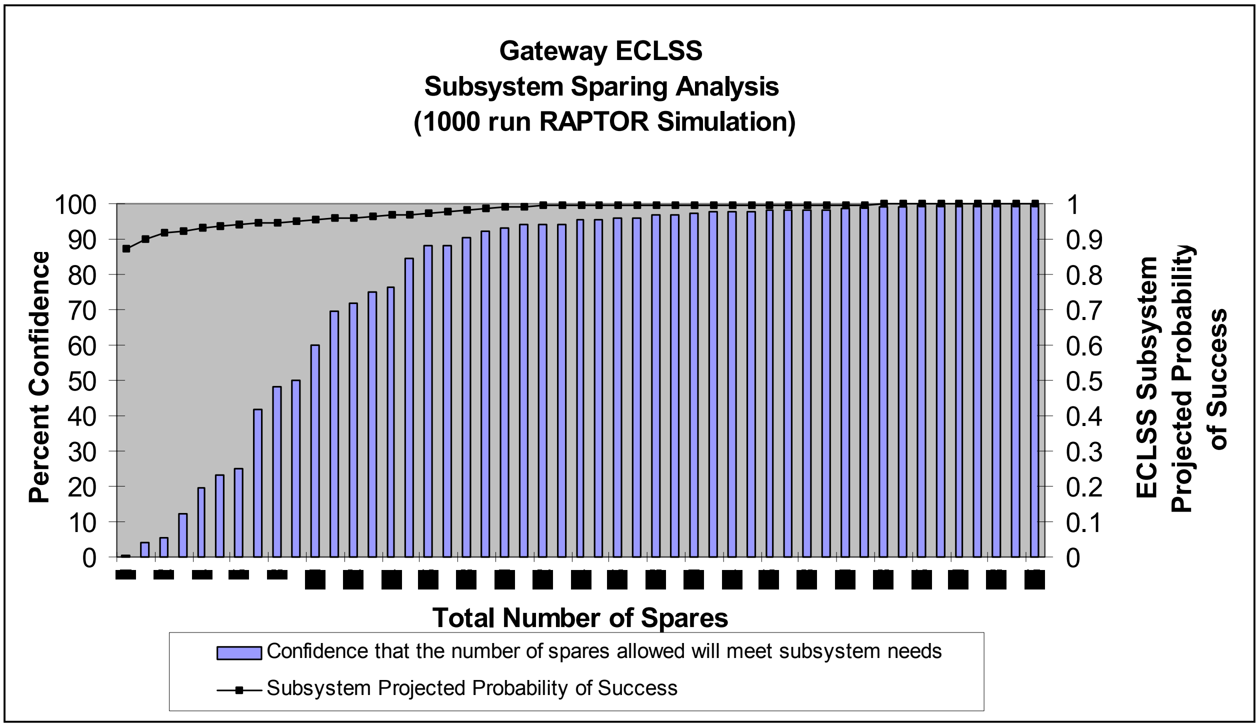


Figure B.3 ECLSS Sparing Analysis

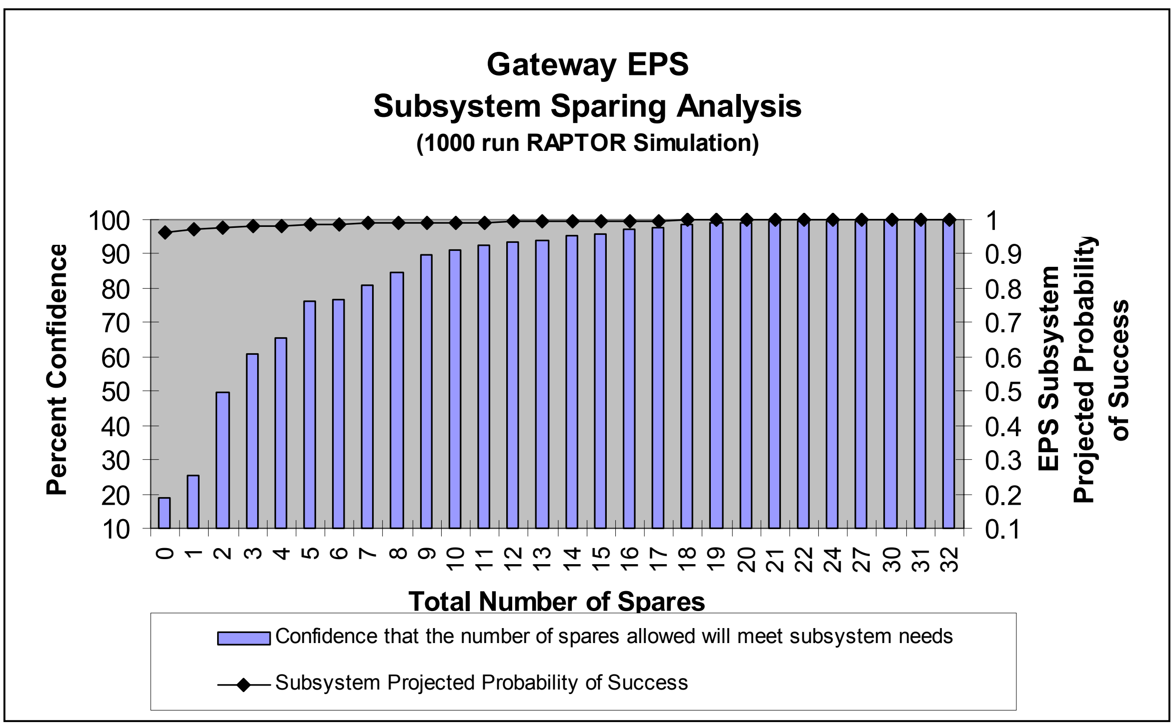


Figure B.4 EPS Sparing Results

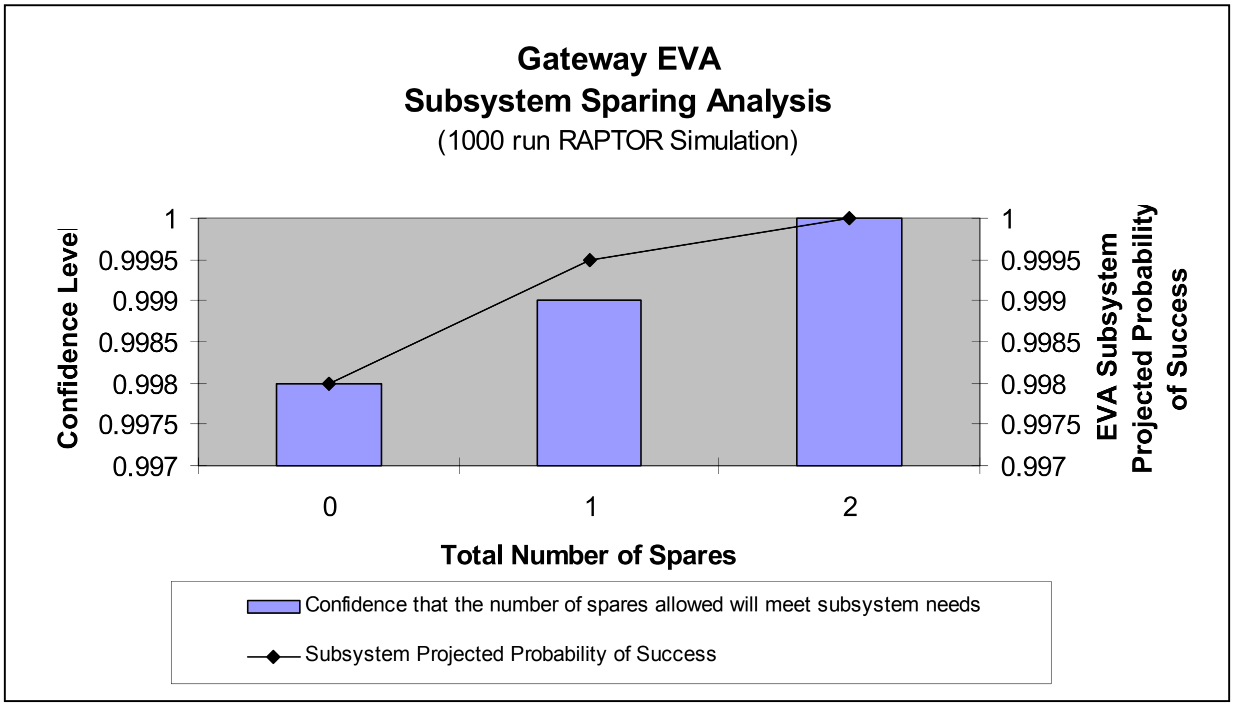


Figure B.5 EVA Subsystem Sparing Results

Table B.1 Preliminary Hazard Analysis

HAZARD NO.	CONDITION	CAUSE	EFFECT	CONTROLS	SUGGESTED DESIGN TEAM MITIGATIONS / ACTIONS / STATUS
GW-01-01	**Contamination in habitable volume**	Leakage of Propylene Glycol or Coolant from the TCS loops or spare media	Mild eye and skin irritation	ECLSS; Leak Detection of TCS media will be through the use of accumulators; Adequate storage of spares/replaced media	Controlled
GW-01-02		Leakage from Power batteries	Leakage from power storage batteries can damage hardware or injure crew members	Adequate design for containment of electrolytic battery media to reduce the possibility of cabin atmosphere exposure or leakage	Controlled
GW-01-03		Payloads/Science/Developmental Test Objectives/Lunar samples	Respiratory, Mucous membrane, skin irritation	1) Crew procedures developed for isolation and containment of samples; adequate monitors 2) Adequate container Design	Controlled
GW-01-04		Tool/Equipment Battery Leakage	1) Injury to crewmember 2) Long-term structural damage from corrosion	Battery design/leakage containment	Controlled
GW-01-05		Inadequate protection from shattering or containment of shatterable material allows release of debris in habitable environment	Crew exposed to particulate contamination	All shatterable material is provided with positive protection to prevent fragments from entering the habitable environment.	Controlled

HAZARD NO.	CONDITION	CAUSE	EFFECT	CONTROLS	SUGGESTED DESIGN TEAM MITIGATIONS / ACTIONS / STATUS
GW-01-06		Leakage of Methane (CH4 Propulsion Fuel) from Propulsion/RCS system	1) Toxic effects to crew 2) Increased likelihood of explosion	1) All Methane lines for Propulsion/RCS will be outside habitable volume to eliminate the possibility of Methane contamination 2) Trace Contanimant Control system for detection of Methane and procedures to isolate leak	Controlled
GW-01-07		Leakage of Human Byproducts	Possible injury to crew	Adequate waste containment system with redundancy	Controlled
GW-01-08		Helium contamination	1) Crew suffocation with high concentrations of Helium 2) No toxic effects to crew with low concentrations of Helium	Leak detection of Helium will be through the use of pressure sensors on the Helium tank	Controlled
GW-02-01	**Electrical Shock**	Inadequate grounding of surfaces accessible to the crew	Injury or death to crewmember	Proper procedures	Controlled
GW-02-02		Improper Circuit/Equipment Design	Injury or death to crewmember	Proper sizing of electrical equipment and wire sizing so steady state currents do not exceed design	Controlled
GW-02-03		Static Discharge	Injury or death to crewmember	Adequate measures for controlling potential	Controlled

HAZARD NO.	CONDITION	CAUSE	EFFECT	CONTROLS	SUGGESTED DESIGN TEAM MITIGATIONS / ACTIONS / STATUS
GW-03-01	**Environmental Hazards**	Excessive thermal conditions	Exceed lower or upper thermal limit of crew/vehicle components	TCS consists of two single loops with redundant pump and heat rejection (radiation) components on each loop	Controlled
GW-03-02		Excessive acoustical conditions	Physiological and psychological effects on crew	1) Adequate noise requirements for equipment in habitable volume 2) Add more acoustic insulation material 3) Crew procedures to use hearing protection in areas of high noise generation	Controlled
GW-03-03		Excessive radiation exposure	Harmful long-term effects on crew health; e.g. Carcinoma	Safe Haven for radiation protection by design; Adequate monitoring of solar activity	Open; Human Factors & Habitability (HF&H) and Radiation
GW-03-04		Inadequate/ inappropriate lighting in habitable volume	Physiological and psychological effects on crew	Acceptable/adequate lighting design	Controlled
GW-03-05		Sharp Edges/Pinch Points	Possible Injury to crewmember	Hardware designed where they will not pinch or snag the crew or their clothing. Exposed surfaces are smooth and free of burrs	Controlled
GW-04-01	**Fire or Explosion**	Flammable Materials	Loss of Crew/Vehicle	Design in accordance with manned space flight Material Selection Requirements, Fire Detection System (FDS)	Controlled

HAZARD NO.	CONDITION	CAUSE	EFFECT	CONTROLS	SUGGESTED DESIGN TEAM MITIGATIONS / ACTIONS / STATUS
GW-04-02		Improper Circuit Design	Loss of Crew/Vehicle	Electrical equipment and wire size is selected so steady state currents do not exceed design standards, FDS	Controlled
GW-04-03		Ignition Sources	Loss of Crew/Vehicle	Design precludes ignition sources, FDS	Controlled
GW-04-04		High Pressure Vessel rupture	Loss of Crew/Vehicle	High pressure vessels will be designed to leak before bursting by material selection/properties; Positive Pressure Relief Valve (PPRV) on pressure vessel and Vehicle Cabin	Controlled
GW-04-05		High concentration of Oxygen	Increased flammability of materials	Redundant O2 Partial Pressure sensing and control units, Material Selection, FDSS. Cabin Atmosphere will be at 62.05 kPa minimum and a maximum of 30% O2 for nominal operations.	Controlled
GW-04-06		Improper power connector design that does not preclude improper mismate / demate.	Loss of Crew/Vehicle	All power connectors are designed such that they cannot be mismated or cross-connected.	Controlled

HAZARD NO.	CONDITION	CAUSE	EFFECT	CONTROLS	SUGGESTED DESIGN TEAM MITIGATIONS / ACTIONS / STATUS
GW-05-01	**Impact/Collision**	Loss of vehicle control during proximity operations with any visiting vehicles or payloads/experiments to the Gateway leads to a collision	Potential loss of Crew/Gateway/Visiting Vehicle/Payload	1) All Gateway and visiting vehicle systems that control vehicle attitude and translation, monitoring of range and range rate, and capture contain redundancy to prevent the possibility of collision. 2) Procedures for safe proximity operations will be maintained to minimize potential for collision.	Controlled
GW-05-02		Impact with Trackable Orbital Debris/Meteroids	Loss of Crew/Vehicle	Operations proceedures to maneuver and avoid debris using RCS	Controlled
GW-05-03		Impact with MMOD	Loss of Crew/Vehicle	MMOD protection designed to shield GW or at least the critical systems. Gateway is designed to meet a certain PNP of .95. This coupled with the crew's ability to escape in the LTV reduces the risk of loss of life to being very unlikely.	Controlled
GW-05-04		Inadequately restrained equipment in Habitable Volume	Loss of Crew/Vehicle	1) Adequate design of restraints 2) Adequate crew procedures for stowage of items	Controlled

HAZARD NO.	CONDITION	CAUSE	EFFECT	CONTROLS	SUGGESTED DESIGN TEAM MITIGATIONS / ACTIONS / STATUS
GW-05-05		Impact of low energy rotating machinery / propelled debris	Injury or death to crewmember	System is designed to include guards and other protective devices to prevent personnel injury, and crew procedures.	Controlled
GW-05-06		Inadequate design results in structural damage	Crew exposed to floating debris or other hazardous condition as result of structural failure of hardware	System is designed to provide positive margins of safety under all loading conditions including crew handling, on-orbit vibration with respect to the required safety factors.	Controlled
GW-05-07		Inadequate positive backout prevention for safety critical fasteners reslults in structural damage.	Injury or death to crewmember	All system safety critical fasteners are designed to prevent backout.	Controlled
GW-05-08		Use of non-conforming fasteners results in release of hardware components	Injury to crewmember	All fasteners conform to an approved fastener intergrity program.	Controlled
GW-05-09		Runaway Remote Manipulator System (RMS)	Loss of Crew/Vehicle	1) Adequate redundancy and fail-safe requirements for RMS design to prevent collision with Gateway/Visiting Vehicles/Payloads. 2) Manual override (kill-switch)	Controlled

HAZARD NO.	CONDITION	CAUSE	EFFECT	CONTROLS	SUGGESTED DESIGN TEAM MITIGATIONS / ACTIONS / STATUS
GW-06-01	**Loss of Habitable Environment**	Compartment depressurization	Loss of Crew/Vehicle	1) Adequate MMOD protection through design. 2) Adequate resources for cabin pressurization in the event of a critical leak. 3) Adequate structural design to prevent excessive leakage in habitable environment.	Controlled
GW-06-02		Loss of O2 Supply	Loss of Crew/Vehicle	Cabin Atmosphere is supplied from three sources of Oxygen	Controlled
GW-06-03		Loss of CO2 removal capability	Loss of Crew/Vehicle	1) Redundant CO2 Removal capability with back up procedures to use solid amine unit from EVA suit. 2) LiOH canisters will be used as a back-up to the primary amine swing beds	Controlled
GW-06-04		Loss of TCS	Loss of Crew/Vehicle	TCS is two Single Loop systems with Fail-Op Fail-Safe Redundancy in all components	Controlled

HAZARD NO.	CONDITION	CAUSE	EFFECT	CONTROLS	SUGGESTED DESIGN TEAM MITIGATIONS / ACTIONS / STATUS
GW-06-05		Loss of Power	Loss of Crew/Vehicle	1) Power system consists two deployable PV arrays, thin film fiber Li-ion battery system, and is Fail-Op, Fail-Safe by design for all phases of flight. 2) Fly-wheels, from the Attitude Control system, will store enough energy to power the Gateway	Controlled
GW-06-06		Toxic Environment	Injury or death to crewmember	1) Materials are Selected in Accordance with manned spacecraft standards. 2) EVA crew member procedures to assure decontamination prior entering Gateway habitable volume. 3) Experiments/Payloads meets standard safety requirements. 4) Trace Contaminate Control System.	Controlled
GW-07-01	**Loss of Vehicle Control**	Loss of Navigation	Loss of Crew and Vehicle	1) Onboard Navigation consists of four INS systems of which any one could perform the Navigation function. 2) DNS and redundant Communicatin system	Controlled

HAZARD NO.	CONDITION	CAUSE	EFFECT	CONTROLS	SUGGESTED DESIGN TEAM MITIGATIONS / ACTIONS / STATUS
GW-07-02		Loss of Vehicle Attitude Sensing	Loss of Crew and Vehicle	Two Star Trackers are provided with back-up capability to use optical equipment	Controlled
GW-07-03		Loss of Attitude Control	Loss of Crew and Vehicle	Vehicle Attitude Control is maintained through fly-wheels. Two-fault tolerance is incorporated for all vehicle rotations.	Controlled
GW-07-04		Loss of Re-Boost Capability	Loss of Crew and Vehicle	Vehicle Re-Boost system should contain adequate redundancy as stated by the Human Ratings Requirement to perform the critical function .	Controlled
GW-07-05		Loss of Vehicle Central Command and Control Capability	Loss of Crew and Vehicle	Vehicle Contains four General Purpose Computers to perform all vehicle functions.	Controlled
GW-08-01	**Detrimental Physiological/Psychological Effects on Crew**	Acceleration, shock, impact & Vibration	Injury or death to crewmember	1)Crew living arrangements will be designed/oriented for worst case g-loading 2) Adequate design of restraints 3) Adequate crew procedures for stowage of items	Controlled
GW-08-02		Effects of Pressure Changes on Crew	Possible Injury to crewmember	Adequate crew safety procedures for EVA pre-breath	Controlled

HAZARD NO.	CONDITION	CAUSE	EFFECT	CONTROLS	SUGGESTED DESIGN TEAM MITIGATIONS / ACTIONS / STATUS
GW-08-03		Illness/Incapacitation of Crew Member	Injury or death to crewmember	Crew Health equipment and procedures	Controlled
GW-08-04		Excessive Noise	Possible Injury to crewmember	1) Adequate noise requirements for equipment in habitable volume 2) Add more acoustic insulation material 3) Crew procedures to use hearing protection in areas of high noise generation	Controlled
GW-08-05		Sharp Edges/Pinch Points	Possible Injury to crewmember	Hardware is designed where it will not pinch or snag the crew or their clothing. Exposed surfaces are smooth and free of burrs	Controlled
GW-08-06		Crew Exposed to Lasers	Possible Injury to crewmember	Lasers are designed such that light intensities and spectral wavelengths at the eyepiece of direct viewing are limited to levels below maximum permissible exposure (MPE).	Controlled
GW-08-07		Interference with Translation Paths. Hardware impinges into translation paths.	Possible Injury to crewmember	Hardware designed to comply with traffic flow and translation paths.	Controlled

HAZARD NO.	CONDITION	CAUSE	EFFECT	CONTROLS	SUGGESTED DESIGN TEAM MITIGATIONS / ACTIONS / STATUS
GW-08-08		Appendage Entrapment in Holes or Latches	Possible Injury to crewmember	Holes and latches meet design requirements designed to prevent entrapment of crew member's appendage.	Controlled
GW-08-09		Inadequate/ inappropriate lighting in habitable volume	Physiological and psychological effects on crew	Acceptable/adequate lighting design. LED's are a proposed solution for lighting.	Controlled
GW-08-10		Inadequate habitable volume	Physiological and psychological effects on crew	Design has an excessive amount currently needed for crew accomodation guidelines.	Controlled
GW-09-01	**Excessive Radiation Levels in Habitable Volume**	Solar Flare/Ionizing cosmic Radiation	Injury or death to crewmember	Safe Haven for radiation protection by design; Adequate monitoring of solar activity	Open; An analysis of the radiation protection of the vehicle's final configuration should be done.
GW-09-02		Non-Ionizing Radiation	Injury or death to crewmember	Minimize radiation emittance and maximize protection of components sensitive to EMI .	Controlled
GW-09-03		Onboard Ionizing Radiation	Injury or death to crewmember	No sources of Ionizing radiation will be used in the GW design	Eliminated
GW-10-01	**Potential Hazards During EVA Operations**	Sharp Edges/Corners and Pinch Points	Possible Injury to crewmember	Hardware designed where they will not pinch or snag the EVA suit. Exposed surfaces are smooth and free of burrs	Controlled

HAZARD NO.	CONDITION	CAUSE	EFFECT	CONTROLS	SUGGESTED DESIGN TEAM MITIGATIONS / ACTIONS / STATUS
GW-10-02		Excessive Non-Ionizing Radiation	Possible Loss of EVA Crew Member	Redundant Inhibits to Ensure Power is Isolated from RF Amps and Electro-Magnets *	Controlled
GW-10-03		Solar Flare/Ionizing cosmic Radiation	Injury or death to crewmember	Safe Haven for radiation protection by design; Adequate monitoring of solar activity	Open; An analysis of the radiation protection of the vehicle's final configuration should be done.
GW-10-04		Crew member collision with other elements attached to the Gateway.	Possible Loss of EVA Crew Member	1) The worksite is clearly defined to minimize the possibility of an EVA crew member being struck by an object. 2) Adequate tools, equipment, and lighting for the safe performance of planned tasks.	Controlled
GW-10-05		Ionizing Radiation	Possible Long-term Injury to EVA Crew Member	No sources of Ionizing radiation will be used in the GW design	Controlled
GW-10-06		EVA touch temperatures	Possible Loss of EVA Crew Member	Adequate Design to meet Touch Temperature Requirements *	Controlled
GW-10-07		Inadequate design for EMU to handle deep space environment (temps, radiation, MM, solar dust).	Possible Loss of EVA Crew Member	Adequate design for EMU to handle deep space environment.	Controlled
GW-10-08		Electric Shock	Possible Loss of EVA Crew Member	Adequate Circuit Design and Grounding *	Controlled

HAZARD NO.	CONDITION	CAUSE	EFFECT	CONTROLS	SUGGESTED DESIGN TEAM MITIGATIONS / ACTIONS / STATUS
GW-10-09		Static Discharge	Injury or death to crewmember	Adequate measures for controlling potential	Controlled
GW-10-10		Inadequate Restraints for EVA crewmember	Possible Loss of EVA Crew Member	Establish EVA Worksites, Pathways, Handholds, and Tether Attachment Points *	Controlled
GW-10-11		Insufficient working volume	Inability to Maintain Payload	Adequate Design for EVA Maintenance or Servicing *	Controlled
GW-10-12		Inadequate grounding	Injury or death to EVA crewmember	Design; Testing; Redundancy	Controlled
GW-10-13		Improper Circuit Design	Injury or death to EVA crewmember	Proper sizing of electrical equipment and wire sizing so steady state currents do not exceed design	Controlled
GW-10-14		EMU encumbrances	Inability to Maintain Payload	Adequate Design for EVA Maintenance or Servicing *	Controlled
GW-10-15		MMOD	Possible Loss of EVA Crew Member	MMOD protection designed to shield EVA suit	Controlled
GW-11-01	**Gateway induced hazards (environments) on visiting vehicles/payloads**	Thruster Plume Impingement on visiting vehicles/payloads (telescopes)	Potential Damage to visiting vehicles/payloads	1)Position of re-boost thrusters eliminate or minimize impingement on visiting vehicles/payloads. 2)Thrusters will not be fired when a visiting vehicle is approaching.	Controlled

HAZARD NO.	CONDITION	CAUSE	EFFECT	CONTROLS	SUGGESTED DESIGN TEAM MITIGATIONS / ACTIONS / STATUS
GW-11-02		Incompatible Electromagnetic Radiation from Gateway to visiting vehicles/payloads (EMI)	Incompatible equipment operations could lead to a hazard for the crew	GW equipment meet the EMI/compatibility requirements for proximity operations with visiting vehicles/payloads	Controlled
GW-11-03		Loss of vehicle control during proximity operations with any visiting vehicles or payloads/experiments to the Gateway leads to a collision	Potential loss of Crew/Gateway/Visiting Vehicle/Payload	1) All Gateway and visiting vehicle systems that control vehicle attitude and translation, monitoring of range and range rate, and capture contain redundancy to prevent the possibility of collision. 2) Procedures for safe proximity operations will be maintained to minimize potential for collision.	Controlled
GW-11-04		GW Attitude Control System conflicting operations with visiting vehicle Attitude Control	Loss of Crew/Vehicle	1) Ops procedures to preclude simultaneous attitude control of mated vehicles 2) Adequate redundancy to assure GW control system is inactive during docked operations	Controlled
GW-11-05		Incompatible pressure control systems of mated vehicles	Potential loss of consumables	Integrate compatabilities of GW and visiting vehicles	Controlled

HAZARD NO.	CONDITION	CAUSE	EFFECT	CONTROLS	SUGGESTED DESIGN TEAM MITIGATIONS / ACTIONS / STATUS
GW-11-06		Inability to close transfer hatch for emergency operations	Loss of Crew/Vehicle	1) Hatch is designed to be easily closed without obstructions 2) Carry-throughs (cabling, power and data) have quick disconnect capabilities	Controlled
GW-11-07		Pressure differential across transfer hatch causes damage when opening	Injury or death to crew member	1) Redundant pressure sensors across hatch for positive verification of pressure equalization 2) Hatch design contains two stage latching mechanisms	Controlled
GW-11-08		Power system incompatibilities between Gateway and visiting vehicles	Damage to Gateway/visiting vehicles EPS equipment	Integrate compatabilities of Gateway/visiting vehicles	Controlled
GW-11-09		C&DH System Incompatibilities	Damage to Gateway/visiting vehicles command and data handling equipment	Integrate compatabilities of Gateway/visiting vehicles	Controlled
GW-11-10		Loss of Space-to-Space Communications during visiting vehicles proximity operations	Damage to Gateway/visiting vehicles	Redundancy in Space to Space communication system	Controlled

Appendix C

Master Equipment List

Lunar L1 Gateway	Launch Mass (kg)				Equip Vol (m^3)		
	% of Inert Mass	Total	Fluid	Dry	Total	Press.	Un-Press.
1.0 Power System	**8%**	**1335**	**0**	**1335**	**27.5**	**9.618**	**17.840**
PV Array		293	0	293	16.2	0.000	16.160
Battery		192	0	192	0.2	0.174	0.000
PMAD		607	0	607	1.0	0.979	0.000
Wiring		243	0	243	10.1	8.465	1.680
2.0 Avionics	**2%**	**251**	**0**	**251**	**0.6**	**0.599**	**0.000**
Attitude Initialization		6	0	6	0.0	0.005	0.000
Voice Peripherals		4	0	4	0.0	0.009	0.000
Communications		24	0	24	0.0	0.020	0.000
Video		8	0	8	0.0	0.005	0.000
Displays & Controls		14	0	14	0.0	0.011	0.000
DMS		35	0	35	0.5	0.503	0.000
Wiring		121	0	121	0.0	0.000	0.000
INS		39	0	39	0.0	0.046	0.000
3.0 ECLSS	**17%**	**2852**	**677**	**2174**	**15.9**	**13.745**	**2.127**
Atmosphere Control		660	478	182	2.290	0.406	1.884
Atmosphere Revitalization		1013	0	1013	2.857	2.857	0.000
Temperature/Humidity Control		88	0	88	6.280	6.280	0.000
Fire Detection/Suppression		22	0	22	0.054	0.054	0.000
Water Management		1027	176	852	4.165	3.922	0.243
Waste		42	24	18	0.226	0.226	0.000
4.0 Thermal Control System	**4%**	**664**	**115**	**548**	**3.4**	**0.258**	**3.133**
ETCS Loop		246	115	131	0.3	0.258	0.004
Shell Heaters		1	0	1	0.0	0.000	0.000
MLI		256	0	256	2.6	0.000	2.556
Radiators		161	0	161	0.6	0.000	0.573
Internal Heaters		1	0	1	0.0	0.000	0.000
5.0 HF&H	**15%**	**2507**	**0**	**2507**	**15.0**	**15.011**	**0.000**
Galley		501	0	501	4.0	4.046	0.000
Crew Quarters		592	0	592	1.7	1.700	0.000
Hygiene Facility		116	0	116	2.2	2.179	0.000
Exercise Facility		305	0	305	0.7	0.737	0.000
Waste Collection Facility		101	0	101	0.7	0.737	0.000
Wardroom		25	0	25	0.1	0.135	0.000
Workstations		88	0	88	1.4	1.366	0.000
Science Equipment		120	0	120	0.5	0.500	0.000
Maintenance Tools		236	0	236	1.2	1.180	0.000
Acoustics		0	0	0	0.0	0.000	0.000
Lighting		76	0	76	0.1	0.090	0.000
Space Medical Facility		348	0	348	2.3	2.341	0.000
6.0 EVA Systems	**5%**	**900**	**0**	**900**	**9.7**	**6.188**	**3.560**
Space Suits		0	0	0	5.7	5.670	0.000

Lunar L1 Gateway	% of Inert Mass	Launch Mass (kg) Total	Launch Mass (kg) Fluid	Launch Mass (kg) Dry	Equip Vol (m^3) Total	Equip Vol (m^3) Press.	Equip Vol (m^3) Un-Press.
Vehicle Support		212	0	212	0.3	0.338	0.000
Translation Aids		123	0	123	3.4	0.000	3.360
Airlock		433	0	433	0.2	0.180	0.000
EVA Tools		132	0	132	0.2	0.000	0.200
7.0 Structure	**44%**	**7354**	**0**	**7354**	**0.2**	**0.233**	**0.000**
Inflatable Skin		1618	0	1618	0.0	0.000	0.000
Core Structure		1356	0	1356	0.2	0.233	0.000
Docking Adapters		1997	0	1997	0.0	0.000	0.000
EVA Work Platform		100	0	100	0.0	0.000	0.000
ORU/Robot Storage		150	0	150	0.0	0.000	0.000
Work Platform Support Struts		264	0	264	0.0	0.000	0.000
Radiation Protection		0	0	0	0.0	0.000	0.000
Cupola		198	0	198	0.0	0.000	0.000
Secondary Structures		1471	0	1471	0.0	0.000	0.000
Interstage Adapter		200	0	200	0.0	0.000	0.000
8.0 Robotics	**1%**	**227**	**0**	**227**	**6.8**	**5.008**	**1.746**
Remote Manipulator System		0	0	0	1.7	0.000	1.746
Robotics Workstation		91	0	91	4.3	4.295	0.000
Robonaut		136	0	136	0.7	0.713	0.000
9.0 Attitude Control System	**2%**	**318**	**0**	**318**	**0.3**	**0.000**	**0.288**
Flywheels		318	0	318	0.3	0.000	0.288
10.0 Propulsion (RCS)	**1%**	**176**	**0**	**176**	**1.3**	**0.000**	**1.292**
Thrusters		54	0	54	0.000	0.000	0.000
Tankage		122	0	122	1.292	0.000	1.292
Subtotal (Inert Mass only)	**100%**	**16,584 kg**	**793**	**15791**	**81 m^3**	**50.660**	**29.986**
30% Margin (Inert System)		**4975**	**238**	**4737**	**15.2**	**15.198**	**0.000**
11.0 Propellant (RCS)		**1268**	**1268**	**0**	**0.0**	**0.000**	**0.000**
12.0 Crew		**0**	**0**	**0**	**0.0**	**0.000**	**0.000**
Total		**22,827 kg**	**2298**	**20529**	**96 m^3**	**65.858**	**29.986**